SAN FRANCISCO PUBLIC LIBRARY
3 1223 00227 3226

PUBLIC
S.F.
LIBRARY

3 1223 00227 3226

621.9 R65g2

Rolt

Gauges and fine measurements

v.2. 299887

MAY 31 '50
149680

Sep16'37 15659

Sep30'37 Pt

BOOK NO. 2
621.9 R65G

ACCESSION
299887

SAN FRANCISCO PUBLIC LIBRARY
VITA SINE LITERIS MORS EST

FORM 3431 30M 8-45

SAN FRANCISCO PUBLIC LIBRARY
3 1223 00227 3226

DATE DUE

MAY 4 1981
SFPL APR 22 '82
SFPL JUL 5 - 1984
SFPL AUG 14 '86
JAN - 4 1997
APR 11 1997

DEMCO 38-297

Digitized by the Internet Archive
in 2022 with funding from
Kahle/Austin Foundation

https://archive.org/details/gaugesfinemeasur0002unse

GAUGES

AND

FINE MEASUREMENTS

BY

F. H. ROLT
M.B.E., B.SC., A.C.G.I., A.M.I.MECH.E.
SENIOR ASSISTANT, METROLOGY DEPARTMENT, NATIONAL PHYSICAL LABORATORY
TEDDINGTON

EDITED BY

SIR R. T. GLAZEBROOK, K.C.B., F.R.S.

VOL. II

LIMIT GAUGES
MEASURING INSTRUMENTS
GENERAL METHODS OF MEASUREMENT

MACMILLAN AND CO., LIMITED
ST. MARTIN'S STREET, LONDON
1929

COPYRIGHT

621.9
R65g 2

299887

PRINTED IN GREAT BRITAIN
BY R. & R. CLARK, LIMITED, EDINBURGH

CONTENTS

CHAPTER I

PAGE

TYPES OF LIMIT GAUGES 1

Internal limit gauges—Cylindrical plugs—Plugs with detachable ends—Difference in behaviour between plug and spherical-ended rod gauges—Adjustable internal gauges.

External limit gauges—Ring and gap types—Solid plate and horseshoe gap gauges—Built-up gap gauges—Adjustable gap gauges.

Société Genevoise machine for setting adjustable gauges.

Depth gauges—Taper gauges—Profile gauges—Position gauges.

CHAPTER II

MICROMETERS 24

Development of micrometers from time of James Watt.

General construction—Ratchet stop and friction drive, adjustments for wear, hardened screws.

General accuracy—Devices for increasing accuracy of reading—Vernier—Special fittings—Direct reading micrometer—Combined inch and millimetre scales—Special types of measuring faces.

Micrometer Heads—Enlarged dial fittings—Use of differential screw—Larger types of micrometers.

Addition of indicator—Adjustable anvils—Built-up micrometers—Johansson and Pitter types.

Tests of micrometers—Accuracy of faces and screw.

Care of micrometers—Necessity for frequent check on zero adjustment, re-lapping faces.

Special types of micrometers—Depth micrometers—Spherometers—Cambridge " Crack " micrometers.

CHAPTER III

MEASUREMENTS WITH SCALES 58

Reference to fundamental line standards—Application of scales to measurements associated with workshop practice—Factors controlling accuracy of scale measurements.

Ordinary steel rules—Types of lines and graduations—Steel tapes—Marking in relief—Correct tension—Use of tapes for circumferential measurements—Corrections necessary for helical effect and thickness of tape—Special tapes for gauging motor rims.

Glass scales—Avoidance of parallax.

Types of magnifying glasses—Hand glasses, watchmaker's eye glasses, binocular type.

PAGE

Uses of scales of measuring instruments—All measurements are reduced to observations on a scale. Typical measuring instruments incorporating a scale—Vernier callipers, height gauges, thickness gauges, wedge gauges.

Scales used on micrometers—Importance of uniform division of dials and correct centering.

CHAPTER IV

Workshop Measuring Instruments 74

Descriptions of: Scribing block, squares, bevel attachments, toolmakers' vices and clamps, vee block, adjustable parallels, callipers and dividers, trammels, feeler gauges, radius gauges, screw-pitch gauges, gauges for threading tools, wire gauges, drill gauges, dial indicator test sets, Zeiss depth gauge, Zeiss optical drill-point tester.

CHAPTER V

Measurement of Taper, Form and Position Gauges . . 88

Use of cylinders and balls—Hoffmann roller gauges. Measurement of taper plug and taper ring gauges—Angle templates. Profile gauges —Optical and mechanical tests—Radius gauges. Position gauges—Use of check gauges, verification by measurement.

Spline gauges—Test of spacing. Castellation gauges—Tests of tooth form and accuracy of spacing—Tests for plate gauges with large radii.

CHAPTER VI

Notes on the Manufacture of Jigs and Position Gauges . 106

Importance of accuracy in jigs and fixtures. Methods of laying off centres of holes with parallel axes—Button method—Disc method—Steel bushes.

Johansson compound slide table.

Jig-boring and measuring machines—Various types made by Société Genevoise utilizing rectangular and polar co-ordinate schemes—Pratt and Whitney machine.

CHAPTER VII

Methods of Testing and Setting Out Angles . . . 124

Bevel protractors—Brown and Sharpe, Zeiss. Gauge clinometers—N.P.L. and Société Genevoise types.

Zeiss optical dividing head—Circular dividing plate by Société Genevoise—Circular dividing machine by Société Genevoise—Automatic correcting device.

Angle measurements by indirect methods—Johansson angle pieces —Cylinders and block gauges—Adjustable taper gaps (Taft-Peirce).

Squares—Methods of testing—Angle plates—Block Squares—Reference squares.

Sine protractor, sine bar—Effect of errors on dimensions—Various patterns—Johansson, Pitter, Taft-Peirce—Adjustable angle plate (Taft-Peirce)—Pitter sine bar fixture.

CHAPTER VIII

Internal Measurements 160

Use of limit gauges—Pin gauges—Inside callipers—Folding wedges —Block gauges with jaws or roller gauges—Steel balls.

Taft-Peirce expanding plug gauge—Newall internal micrometer—Inside micrometer calliper—Brown and Sharpe, Zeiss, Pitter types.

Indicating instruments — Hirth minimeter, Zeiss "passimeter", "Subito" cylinder gauge, Zeiss internal comparator.

Incorrect design of certain types of three-point gauges.

CHAPTER IX

INTERNAL MEASUREMENTS (*continued*) 180

Descriptions of various measuring machines — Société Genevoise, Wickman, N.P.L. "chord contact" and "displacement" types.

CHAPTER X

TESTS FOR FLATNESS AND STRAIGHTNESS 190

The machining of flat surfaces as a copying process—Accuracy depends upon the "ways" of machine tools and is controlled finally by master surface plates.

Whitworth's method of producing flat surfaces.

Designs of surface plates—Ageing to prevent warping—Special rotatable surface plate—Rigidity and stiffness of plates—Multiple supports.

Methods of testing flatness—Comparison with a surface plate—Use of optical flats—Straight-edges and their uses—Plate and knife-edge forms. Flexure of straight-edges—Best position for supporting. Method of testing a surface by means of a sensitive level—Autocollimation method—Use of the free surface of a liquid as a true plane of reference —Stretched wire method for testing straightness—Appliances by Cambridge Instrument Co. for testing flatness and straightness—Optical test for parallelism of surfaces.

CHAPTER XI

MEASUREMENTS WITH OPTICAL INSTRUMENTS 218

Travelling microscopes—Cambridge instrument—N.P.L. design. Rectangular co-ordinate measuring microscopes — Société Genevoise microscope — Herbert optical measuring machine. Zeiss thickness measurer. Zeiss direct-reading microscope.

Optical projection apparatus — Early developments — Standard horizontal apparatus (N.P.L.)—Special applications—Vertical projection apparatus (N.P.L.)—Lewbeck projection microscope.

Factors controlling definition of projected images.

CHAPTER XII

ELECTRICAL DEVICES USED FOR MEASURING 244

Indication of contact between fixed and moving parts of measuring device by electrical means—Tomlinson's "grid contact" method—Sensitive measuring device depending upon electrical indication of contact.

Rayner's application of thermionic valve to the measurement of small displacements—Whiddington's "ultra-micrometer"—Dowling's use of oscillatory valve circuit to measurements—Thomas' method of measuring small displacements—Electric telemeters—Application of the change in resistance of a pile of carbon plates, when compressed, to the measurement of small movements.

PAGE

CHAPTER XIII

MEASUREMENT OF FINE WIRES AND FIBRES 258

Limitations of ordinary mechanical and optical methods.

Eden's cantilever method—Tomlinson's method of measuring quartz suspension fibres—Barrell's optical scheme for same—Cambridge Inst. Co.'s machine for measuring fibres.

CHAPTER XIV

NOTES ON DESIGN OF MEASURING INSTRUMENTS 266

Geometric location—Hole, slot and plane—Three vee-grooves. Degrees of freedom. Geometric slides—Use of hardened ground rods—Vee-grooves—Principle of alignment—Effect of flexure of measuring machine beds upon accuracy—Thrust of micrometer screws—Methods of avoiding periodic errors—Uses of flexible steel strips in measuring devices—Micrometer screws—Material, form of thread, "running in"—Backlash—Fine adjustments.

CHAPTER XV

MEASUREMENT OF GEARS 289

Zeiss optical gear-tooth calliper—Pratt and Whitney "Odontometer"—Maag tooth-measuring instrument.

Maag gear-tooth profile-testing appliance—Zeiss involute testing machine—Saurer gear-testing apparatus—Zeiss optical gear tester—Wickman gear-measuring machine.

CHAPTER XVI

MEASUREMENT OF GEARS (*continued*) 311

N.P.L. gear-measuring machine — General description — Special pantograph—Measurement of circular pitch—Group records—Cumulative and individual pitch errors—Effects of irregularity—Effect of pitch errors on tooth thickness.

Measurement of radial alignment of teeth, axial alignment in case of spur gears.

Tests for shape of teeth—Measurement of base circle diameter.

Application of machine to bevel gears and other types.

Method of recording uniformity of motion transmitted by a pair of gears.

Hob-measuring machine.

APPENDICES

I. WIRE AND PLATE GAUGES 335

II. MEASUREMENTS OF A ONE-INCH CYLINDRICAL RING GAUGE BY VARIOUS METHODS 338

III. MATHEMATICAL INVESTIGATION OF THE FORM OF A STRAIGHT-EDGE BENDING UNDER ITS OWN WEIGHT WHEN SUPPORTED HORIZONTALLY ON TWO SYMMETRICALLY PLACED SUPPORTS . 340

IV. NOTE ON THE TESTING OF A CIRCULAR DIVIDING MACHINE . 347

INDEX 351

CHAPTER I

TYPES OF LIMIT GAUGES

The commonest types of limit gauges are those used for checking plain cylindrical work, internal and external. These take various forms according to the shape and size of the work to be tested. A few typical examples of each are referred to below.

I. Internal Limit Gauges

(i) Cylindrical Plug Gauges.

For holes up to 1 or 2 inches in diameter, the limit gauges usually take the form of a pair of plugs made either in one piece, as in Fig. 1, or as separate gauges.

Since the " not go " plug is intended to function only towards its extremity, it is general practice to make its length shorter than that of the " go " plug. When using such a gauge, this obvious difference between the two ends serves as a useful distinction, and obviates having to refer to the marking on the handle. In gauging " through " holes, time can be saved by having both " go " and " not go " plugs at one end of the gauge, as in Fig. 2.

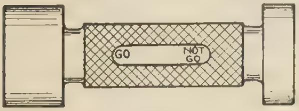


Fig. 1.

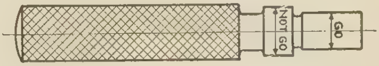


Fig. 2.

(ii) Plug Gauges with Detachable Ends.

The gauge shown in Fig. 1 is made solid. Sometimes, especially for sizes above an inch or so, the gauging cylinders are made separately, and are attached by a central screw to a mild steel handle. When the plugs of such a gauge become tapered due to wear, it is possible to reverse them on the handle and thus prolong the useful life of the gauge. In addition to this advantage, cylinders made separate from the handle can be produced very economically by grinding and lapping in quantities on special machines,* such as are used by Messrs. Pratt and Whitney for producing their "trilock" plug gauges (see Vol. I. p. 118).

(iii) Larger Gauges.

When gauges reach a diameter of about 3 inches, it becomes necessary for ease in handling to reduce their weight as much as possible. This is usually done by drilling a number of holes through the plug parallel to its axis as at A, Fig. 3, or by recessing the ends as at B.

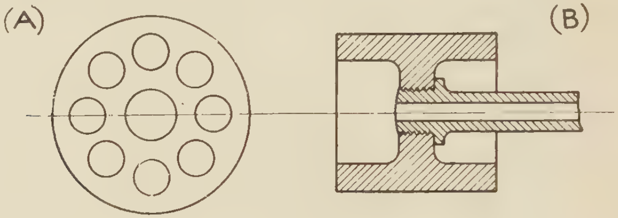


FIG. 3.

Above 6 inches, plug gauges become too unwieldy and awkward to handle, and are replaced either by bars having cylindrically-formed ends, as at A in Fig. 4, or spherical-ended rods, as at B.

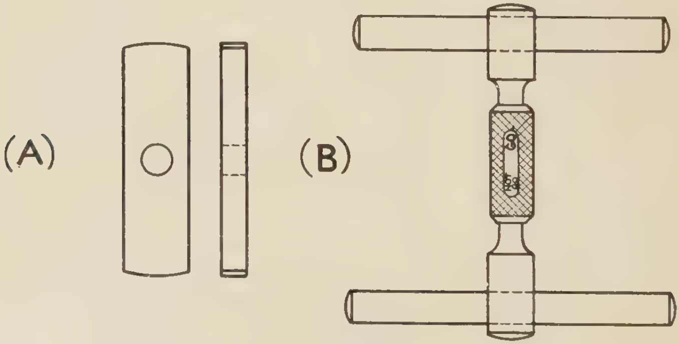


FIG. 4.

---

* For description of machines and methods of producing such cylinders see "Precision Cylinder Lapping," by P. M. Mueller, *Amer. Mach.*, vol. 63, p. 439 (1925).

(iv) Difference in Behaviour of Plug and Spherical-ended Rod Gauges.

In testing a hole which is not truly circular in section with limit plug gauges, the test is really applied only to its minimum diameter. No definite information is obtained as to its departures from circularity, and its maximum diameter could exceed the upper limit without the part being rejected on the " not go " test. It is evident that, provided a hole is within limits across even one diameter at the ends, the " not go " plug could not be inserted in it and the work would be passed. A burr at the entrance of an oversize hole might, therefore, easily lead to its acceptance so long as the "go" gauge entered it.

If a hole accepts the " go " plug gauge it is clear that no diameter is below the lower limit. Interchangeability is thereby assured, but if the part is of such importance that it is necessary to ensure that it does not exceed the upper limit across *any* diameter, instead of using a plug gauge for the " not go " test, the latter should be performed with a spherical-ended rod gauge which would need to be tried in the hole in various positions.

(v) Adjustable Internal Gauge—Johansson Type.

Up to the present we have been concerned with gauges of definite sizes. There are, in addition, types of internal gauges whose sizes may be varied and adjusted within a limited range. This feature provides not only a means of setting the sizes of a pair of limit gauges to suit any particular series of tolerances on a given size of hole, but also enables the gauges to be restored to correct size after wear.

The Johansson type of adjustable gauge consists of a cast-iron frame A (Fig. 5) which is screwed to a handle and houses a pair of hardened steel gauging anvils B, the ground shanks of which are a good fit in a hole passing through the frame. The size over the anvils is adjusted by a fine-threaded screw C. This controls the position of a conical plug D, forming the abutment for the inner ends of the anvils which are bevelled to suit the angle of the cone. The anvils are prevented from rotating, and, after adjustment, can be locked in position by set-screws E, the ends of which bear on flats ground on the shanks. After setting and locking the anvils, the heads of the three screws can be sealed to prevent tampering.

Centres are provided in the ends of the frame and the handle so that the anvils can be ground to correct cylindrical form *in situ*. Actually they are reduced to a size somewhat smaller than that for which the gauge will be required, after which the adjustment is used to bring them to the desired dimension. If, as the result of wear, the surfaces of the anvil become out of true, they can easily be reground and adjusted once more to size.

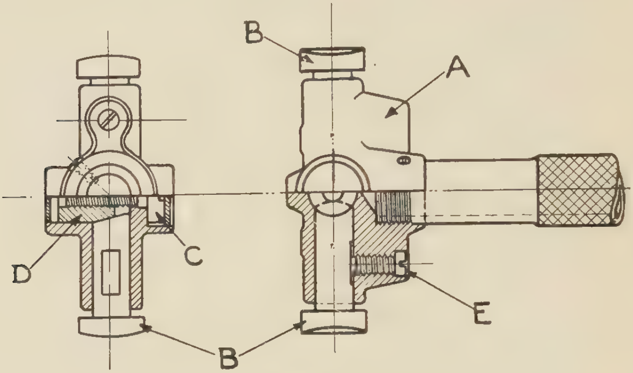


Fig. 5.

(vi) **Pedersen Type Adjustable Limit Gauge.**

Another type of internal limit gauge, the ends of which can be adjusted within certain limited ranges, is of the form shown in Fig. 6.

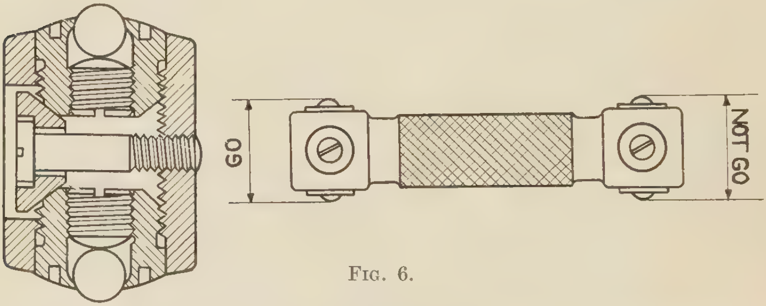


Fig. 6.

The gauging surfaces at each end are formed by a pair of hardened steel balls. The method of adjusting the size will be gathered from the enlarged section. After setting the positions of the plugs holding the balls, they can be locked by the conical washer under the head of the central screw. Should the gauging surfaces of the balls become damaged at any time, it is a simple matter either to turn them in their sockets and obtain fresh positions on their surfaces, or to substitute new balls.

(vii) Pitter Type Adjustable Limit Gauge.

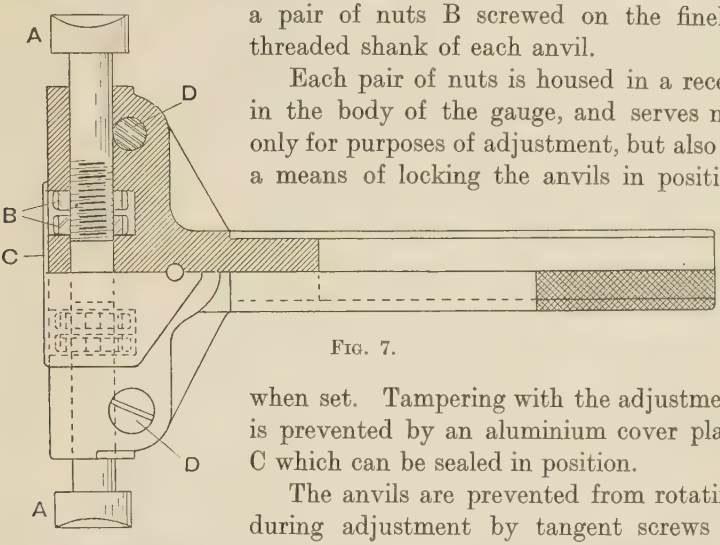


Fig. 7.

In the Pitter type of adjustable internal gauge, the size over the outer cylindrical surfaces of the anvils A (Fig. 7) is controlled by a pair of nuts B screwed on the finely-threaded shank of each anvil.

Each pair of nuts is housed in a recess in the body of the gauge, and serves not only for purposes of adjustment, but also as a means of locking the anvils in position when set. Tampering with the adjustment is prevented by an aluminium cover plate C which can be sealed in position.

The anvils are prevented from rotating during adjustment by tangent screws D bearing against flats, ground on the shanks. The faces of the anvils, are, of course, ground with the gauge assembled, the radius of curvature being slightly less than the minimum size for which the gauge is intended.

For sizes between $2\frac{1}{2}$ and 4 inches the range of adjustment provided is $\frac{1}{4}$ inch on each gauge, and only one anvil is made adjustable. Larger sizes up to 6 inches have $\frac{1}{4}$-inch adjustment on each anvil.

II. Limit Gauges for External Measurements

(i) Ring and Gap Types of Gauges.

Gauges for checking external measurements are of either ring or gap form. The use of the former is confined to cylindrical or spherical work, but the latter, besides serving for lengths, thicknesses, etc., can also be used for the same purpose as ring gauges. A gap gauge is more convenient than a ring for controlling the production of cylindrical work ; it can be applied to the part without removing it from the machine, and, in addition, it affords a means of detecting lack of circularity and parallelism.

For the final inspection of plug work the best arrangement is to use a ring gauge for the "go" and a gap for the "not go" test. This ensures that the work is everywhere small enough, which is of the greatest importance from the point of view of interchangeability, and, if the gap gauge is applied to the work several times, there is a fair chance of detecting any diameters below the lower limit. To use a ring gauge for the "not go" test is to risk the possibility of passing work which is too small except at a local region.

The substitution of a gap for the "go" ring gauge is permissible, provided the inspector uses care to search for high diameters, and provided there is no possibility of the work being lobed.* Where interchangeability is vital, the use of a ring gauge for the "go" test should not be departed from so far as the final inspection of plug parts is concerned.

Ring gauges up to an inch or so in diameter are generally made of tool steel, hardened throughout. Larger sizes are often made of mild steel, either case hardened or lined with a hardened steel bush.

From the point of view of ease in handling, it is clearly desirable to reduce the weight of metal in a ring gauge to a minimum. This should not be carried too far, however, otherwise the ring is liable to stretch and distort in use due to lack of strength. For this reason it is best to keep the outside diameter as large as possible, and to obtain any necessary reduction of weight by drilling a series of holes round the ring.

Where the tolerance on the work is small, "go" ring gauges should be finished by lapping. This process not only enables gauges to be brought to size with more certainty, but also renders them less susceptible to initial wear on account of the smoothness of the surface.†

(ii) Solid Types of Gap Gauges.

Broadly speaking, there are three types of gap gauges—solid, built-up and adjustable. The simplest of the solid type is made from steel plate, as in Fig. 8. It is easily made from ground flat stock, and serves the purpose of a workshop gauge for sizes up to about an inch. Other solid types of gap gauges are shown in Fig. 9.

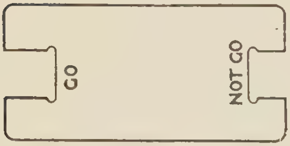


FIG. 8.

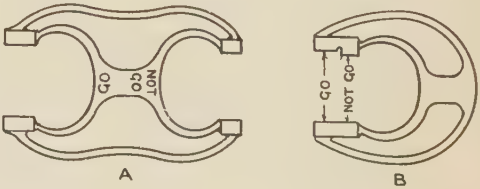


FIG. 9.

---

* See Vol. I. p. 122.

† See Vol. I. p. 133.

These are made from forgings or malleable castings, so designed as to have a minimum weight consistent with ample rigidity. The "go" and "not go" gaps are sometimes on separate gauges, but more often are combined either in the form of a double-ended gauge A, or as a single-ended gauge B, having one jaw flat and the other stepped by an amount equal to the tolerance on the work. The latter clearly has the advantage of saving time in applying the two gaps to the work.

(iii) Built-up Gap Gauges.

For ease in manufacture, the built-up type of snap gauge, shown in Fig. 10, possesses obvious advantages. It consists of a pair of side plates A and B, attached by screws to the parallel faces of a block C which acts as a distance-piece. The inner face of one of the side plates, A, is ground and lapped in one plane, whilst that of the other is prepared in the same manner, but is stepped down at one end by an amount equal to the work tolerance. The block C has its faces brought accurately parallel by "spot-grinding," and is finally lapped to the size required for the "not go" gap. Sound contact is ensured between the side plates and the blocks by "wringing" joints which are maintained by the screws, as shown. The three main parts of the gauge are, of course, hardened, and, in the event of wear on the side plates, they can be readily detached for re-lapping.

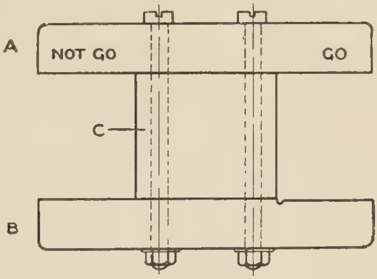


FIG. 10.

A still further simplification can be obtained by making two independent gauges, one for the "go" and the other for the "not go" size. The end plates then need project beyond the block only at one end, and any difficulty in grinding and lapping the step on the lower side plate is eliminated.

(iv) Adjustable Gap Gauges.

We come now to types of adjustable gap gauges, of which there are many varieties. The simplest form consists of a cast-iron horse-shoe frame, Fig. 11, having on one side a pair of fixed contact faces screwed or driven into the frame, and on the other a pair of adjustable anvils screwed into fine-threaded holes in the frame. The distances between the opposing anvils can therefore be set to any particular limits within the range available, and, after being set, the movable anvils can be clamped in their holes by some suitable means. This type of gauge serves for general use in the shop, but suffers from the disadvantage of being easily tampered with. In addition, owing to the difficulty of grinding the faces of the movable anvils square to the axes of their screwed shanks, it is not an easy matter to maintain satisfactory parallelism between the jaws for all adjustments.

Gauges of the above type are made up to sizes as large as 60 inches. Up to 6 inches the available range for setting is usually about $\frac{1}{2}$ inch ; for larger sizes it is extended to about an inch. To facilitate handling, the frames of the large sizes of these gauges are generally made of light alloy. The contact faces are, of course, hardened steel.

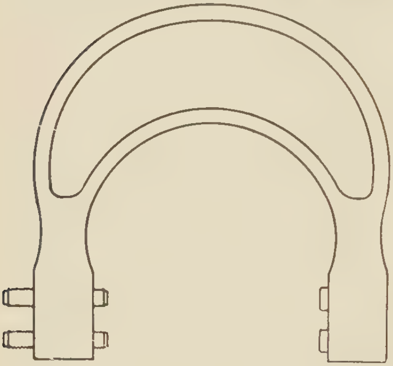


Fig. 11.

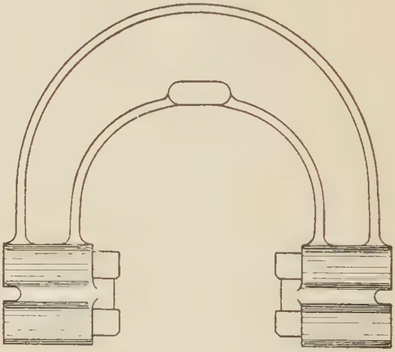


Fig. 12.

An improved form of adjustable limit gap gauge, due to A. C. Wickman, in which the adjustment of the anvils is made by sliding them in the frame without rotation, is shown in Fig. 12. Details of the construction of the anvils and the method of adjustment will be gathered from Fig. 13. The anvils A are rectangular in shape, and have cylindrical shanks which are close working fits in holes bored in the frame. They are prevented from rotating by an abutment B on the frame. The outer ends of the holes in which they fit are tapped with a fine thread for the adjusting screw C. The locking screw D passes through a clearance hole in the latter into a hole tapped in the shank of the anvil. Conical recesses are formed in the ends of the shank and in the adjacent face of the adjusting screw, and between these faces is placed a steel ball F, drilled to allow passage of the locking screw.

The adjustment of the gauge is made by first releasing the locking screw D a turn or two ; the adjusting screw C can then be moved in either direction by means of a special key, Fig. 14, the two prongs of which are inserted through holes in the head of the locking screw. The position of the anvil is adjusted so that the setting gauge is rather a tight fit between the jaws. In tightening the locking screw, the anvil is then drawn back on to the steel ball, and the slight "give" due to elastic compression at the contact of the ball and its seatings provides a sensitive adjustment for the final position of the anvil. Having set the anvils, interference with the adjustment is prevented by the insertion of lead seals E over the heads of the locking screws.

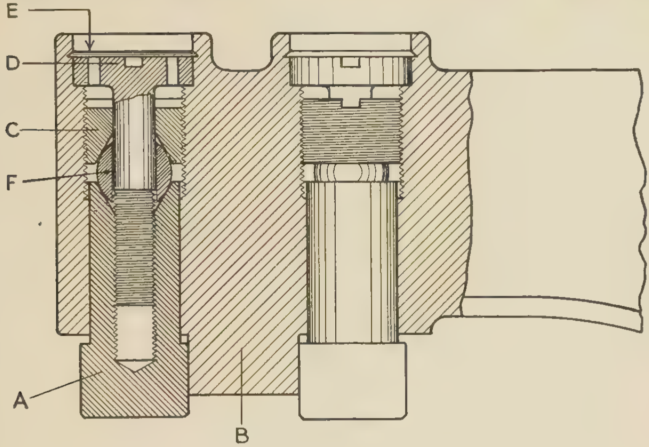


FIG. 13.

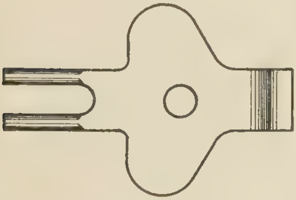


FIG. 14.

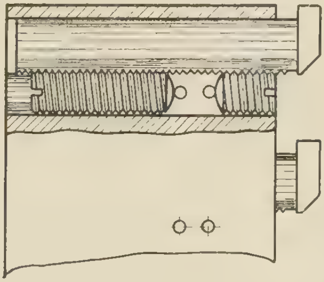


FIG. 15.

There are many varieties of the type of gauge just described, the main difference being in the method of adjusting the anvils. The scheme used by Messrs. Pratt and Whitney is of a very simple character. Each of the anvils has a partial screw thread cut along one side (Fig. 15) with which engage two headless set-screws, working in a reamed hole, with their inner ends butting against stop pins. The adjustment is made by loosening one screw and tightening the other: when the screws are finally set they automatically become locked, and the anvil is held definitely in position.

The method of adjustment used by the Société Genevoise will be seen from Fig. 16. The rear end of the hole in which the anvil is located is tapped with a fine thread into which a split screw B fits. The latter can be screwed up with a special key, and serves to advance the anvil, which is prevented from rotating by a key A. Having set the anvil, it is held in contact with the screw by means of a locking screw C with a conical head. The action of tightening this screw also tends to expand the adjusting screw, and thus locks it in position.

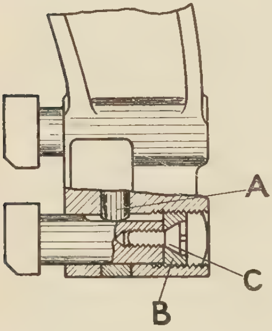


Fig. 16.

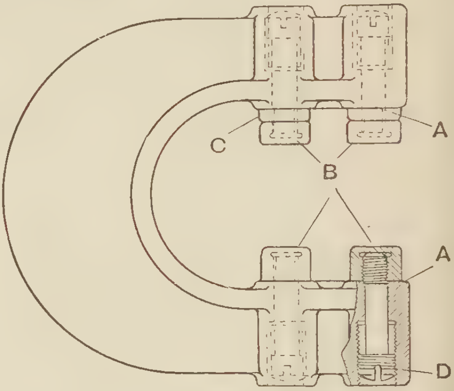


Fig. 17.

A rather interesting form of adjustable limit gauge is one patented by A. J. C. Brookes, and shown in Fig. 17. The faces A of the frame are ground truly parallel and at certain definite distances apart, such as 1·0000, 2·0000 inches, etc., according to the size of the gauge. The anvils B consist of hardened steel caps made to a definite thickness. The adjustment for size is obtained by the provision of a set of distance pieces C, which can be inserted either singly or in combination beneath the anvil before the latter is pulled up into position by the locking screw D, which has right and left hand threads at the ends.

The distance pieces are manufactured by a process similar to that devised by the same patentee for the production of block gauges.* For convenience they are made in the following series of sizes, which lend themselves readily to the process of building together into combinations of any size to four places of decimals in inches:

---

* See Vol. I. p. 82.

·1001, ·1002, ·1003	·1009
·101, ·102, ·103	·109
·11, ·12, ·13	·19
·1, ·2, ·3	·9

With a set of frames, anvil pieces and two sets of distance pieces, it is possible by this scheme to set up a limit gauge to any required sizes without reference to any other end standards.

By making the anvils in quantities, the makers—The Pitter Gauge and Precision Tool Co.—claim to be able to supply new ones at a cost which makes it more economical to discard worn anvils rather than to attempt regrinding their faces. Moreover, since the anvils are made to standardized thicknesses, the substitution of new anvils has the distinct advantage of restoring the gauge to its original basic dimensions. True parallelism between the faces is also ensured.

Appreciable time is stated to be saved in the inspection of large numbers of parts by the use of gap gauges of the design shown in Fig. 18, which is produced by The Greenfield Tap and Die Corporation, U.S.A. Instead of four adjustable anvils, the gauge has only two, those on one limb of the frame being replaced by a long, solid jaw projecting well beyond the "go" gap, which thus forms a base upon which the work can be rested and properly located before moving it towards the gauging anvils. A foot is cast on the frame of the gauge so that, if desired, it can be stood upon the bench, leaving both hands free to manipulate the work. The ring at the back serves as a handle on occasions when it is more convenient to try the gauge on the work.

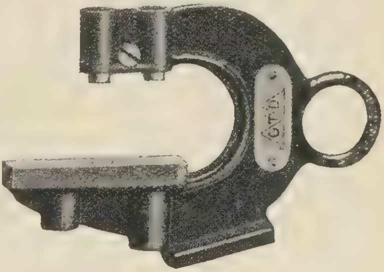


Fig. 18.

(v) Elastic Deformation of Gap Gauges.

Trouble is sometimes experienced due to springing of the jaws of gap gauges. It arises most frequently with larger sizes, where the rigidity of the frame often suffers in the endeavour to reduce the weight of the gauge to a minimum. Any tendency for the gauge to spring makes it difficult in the first instance to set to size, and, in actual use, allows work to be passed which is strictly too large without the operator being conscious of using any undue effort in passing the work through the "go" gap.

If, when adjusting a new design of gap gauge to size in the tool or inspection room, it is found to be rather an indefinite operation owing to springiness, the gauge could be subjected to a series of tests with the view of determining the variation in size caused by known forces tending to separate the anvils. The results of such tests would serve to differentiate between gauges of different designs, but it would be a matter of further experiment to decide just what lack of rigidity could be safely tolerated in practice for any given size of gauge, when used under normal conditions. In making such experiments, it would have to be remembered that the pressure required to force an oversize piece of work between the " go " anvils would be influenced not only by the actual amount of interference and the rigidity of the frame of the gauge, but also by such factors as the grade of smoothness of the surfaces of the anvils and the work, whether they are dry or lubricated, and the degree of parallelism of the anvils. The latter is of importance, as a widening of the distance between the anvils towards the entry side would clearly facilitate the passage of the work on account of the powerful wedging effect which would arise.

(vi) Machine for Setting Gap Gauges.

A unique type of machine was introduced a few years ago by the Société Genevoise for accurately setting their adjustable gap gauges. Ordinarily, this operation is done with the help of end gauges of the block type—a method which has the advantage of simplicity, but which deteriorates appreciably in accuracy when dealing with the larger sizes of gauges. Up to one or two inches, a difference of 0·0001 inch in the size of gaps can be readily detected, but on 6-inch gauges the discernible difference would be hardly less than 0·0002 inch. The unavoidable handling of the gap gauge and the standards also gives rise to the risk of additional uncertainty due to temperature changes.

In the machine to be described, the reference standard is a calibrated scale, the accuracy of which does not become impaired with repeated use as is the case with end gauges ; moreover, no handling of the standard or of the gap gauge is necessary during the operation of setting and measuring.

The machine is designed to deal with gap gauges ranging from $\frac{1}{2}$ up to 10 inches, and an accuracy of 0·0001 inch is claimed for its performance.

The machine is shown in Fig. 19. The general principle will be grasped when it is stated that the gauge is held in a fixed position on the machine, and the distance separating the anvils is obtained by measuring the displacement of a ball of known diameter between the faces, by means of a scale. The latter is attached to the same carriage as the ball, and is viewed under a fixed microscope having a micrometer eyepiece.

The gauge is supported in a vertical position at the front of the machine. The right anvil is held in a supporting clip, similar to A, which is bolted to the front face of the machine, whilst the opposite anvil simply rests upon a similar bracket which can be moved along the upper edge of the face to suit the particular size of the gauge to be dealt with. This method of supporting the gauge avoids any distortion of the frame which would be likely to affect the distance between the anvils to any appreciable extent.

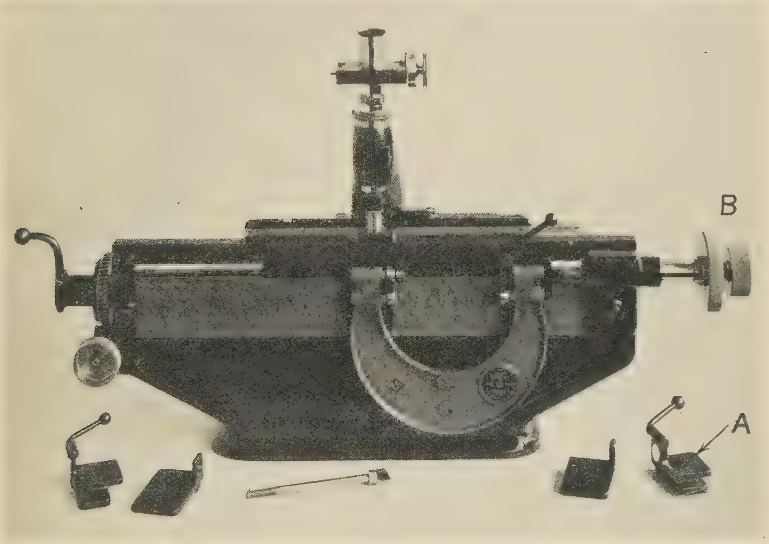


Fig. 19.

The adjustment and locking of the right anvil is effected by two concentric screw-drivers B, passing through a fixed bracket on the machine. Since this anvil is rigidly held in its supporting clip, it will be understood that any adjustment of the anvil with respect to the frame of the gauge causes the latter to move bodily endwise, carrying with it, of course, the left anvil.

The internal construction of the machine will be gathered from Fig. 20, which shows a plan and a side elevation in section.

The scale A and contact lever B are carried on the slide C, which can be traversed along "vee and flat" ways on the bed by a screw D. The latter has a handle E and a tangent screw attachment F for fine adjustment. The contact lever is carried between a pair of vertical

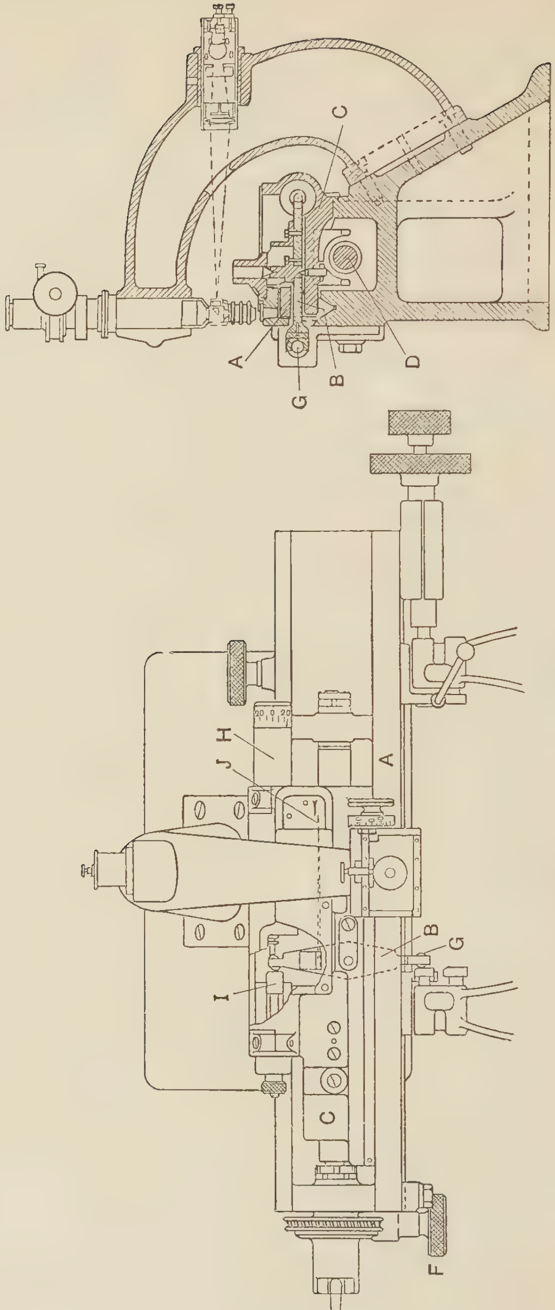


FIG. 20.

pivots, and is furnished at the front end with a steel ball G, about 1 cm. in diameter. The rear end makes contact with the plunger of a sensitive indicator H, which is also fixed to the slide. Readings of the microscope on the graduations of the scale are made only after the position of the slide has been adjusted so as to bring the pointer of this indicator to its central zero mark, whether contact is being made with the right or the left anvil.

To make a setting on the right anvil, the slide is moved towards it until contact occurs between the ball G and the anvil face. The motion of the slide is continued until the pressure on the lever brings the indicator needle to its zero mark. To set on the opposite anvil, a spring-plunger I has to be brought into action. The pressure of this plunger on the rear end of the lever opposes and overcomes that of the indicator, so that the ball G is deflected to the left of its mid position, ready to be brought back to zero when the slide is moved to the left.

In order to give warning of the approach of a setting, the lever itself is provided with a pointer J. When the tip of this arrives at a fixed index mark, the fine adjustment of the traversing screw is brought into action ready for the final adjustment as given by the more sensitive indicator.

In adjusting the jaws of a gap gauge to a given dimension, they are first set roughly by a scale so as to be about 0·02 to 0·04 inch too far apart. Having mounted the gauge in the machine with the left anvil locked, a setting of the ball is made on the right anvil followed by a reading of the microscope taken on the nearest twentieth of an inch division on the scale. Since the graduations on the drum of the microscope represent 0·0001 inch, the reading can be taken by estimation to 0·00001 inch. The slide is then traversed to the left, and set so that the reading on the scale, supplemented by that on the microscope, is equal to the initial reading plus the required distance between the anvils minus the known diameter of the ball. Adjustment of the right anvil is then carried out by the screw-driver fitting until the left anvil is brought up to the ball and the indicator registers zero. Care has to be taken to see that in finally locking the anvil the setting is not disturbed. As a final check, the reading on the right anvil should be repeated.

To set the other pair of anvils, the gauge has to be reclamped in the machine so as to bring them in line with the ball.

The supports for the gauge are so designed as to bring the ball opposite the centres of the anvil faces. If it is required to check the uniformity of the distance between the anvils at different parts of their faces, it would be necessary to provide other supports so as to vary the point of contact of the ball on the faces.

Since the pressure on the ball is reversed between the two settings on a pair of anvils, the elimination of backlash at the pivots carrying the lever and in the mechanism of the indicator has to receive particular attention. Rigidity of the lever is also of importance for the same reason.

The scale of the machine is of 58 per cent nickel-steel, which, besides having a coefficient of linear expansion closely equal to that of the material of the gauges, possesses the advantage of being free from tarnishing. Each scale is accompanied by a calibration table giving the errors of its graduations to 0·00001 inch.

(vii) Indicating Gap Gauges.

In gauging work, either during machining or in the final inspection stage, it is sometimes necessary, particularly where selective assembly is to be used, to be able to state the actual error from the basic size. To obtain this information, the usual limit gap gauge is replaced by some simple form of indicating comparator. This is set to read zero on a piece of true basic size, and indicates directly the errors of the parts as they are passed through it in succession. Such comparators (examples of which are given in Vol. I. p. 328 of this work) usually consist of a base plate, or fixed anvil, above which is supported some type of "indicator", of which the dial form is perhaps the most familiar.

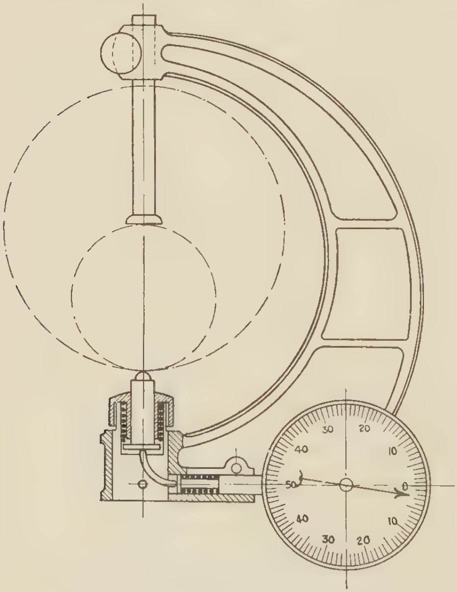


Fig. 21.

The same principle is adopted in the "Subito" gap gauge, Fig. 21. The bow-frame carries at the upper end an adjustable anvil, whilst the lower, ball-ended anvil is connected with a dial indicator by a quadrant-shaped rod. The latter is circular in section, and is a good working fit axially in a hole of square section which is formed between two blocks.

Another design of indicating gauge, made by Messrs. Carl Zeiss, is shown in Fig. 22. The bow-frame has, as usual, two anvils ; the one on the right is fixed, whilst the other can move endwise in a well-fitting bush. The position of the movable anvil is recorded on a scale by a pointer, which is operated through a magnifying mechanism consisting of a pivoted lever having at one end a toothed sector engaging with a pinion attached to the axis of the pointer. To prevent unnecessary wear on the anvils, the movable anvil can be withdrawn slightly when it is desired to insert work between the faces. This is done by finger pressure on the small plunger A, the motion being transmitted to the anvil by a lever, as shown. The fixed stop B acts as a register for cylindrical work.

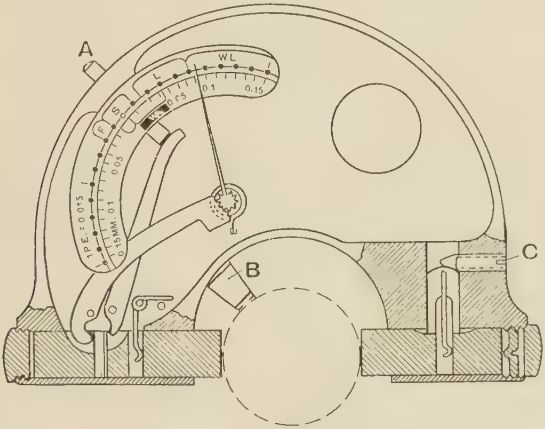


Fig. 22.

The scale of the instrument has fifteen divisions on each side of a central zero, each representing 0·01 mm. In addition to these graduations, the scales are sometimes marked to indicate standard limits for the different grades of fits standardized in Germany.

The instrument is set to read zero with an end gauge of basic size between the jaws, the adjustment being made by moving the right-hand anvil by means of a screw at the outer end. When set, this anvil is locked in position by the screw C, the conical point of which depresses a plunger which bears upon the shank of the anvil.

This type of gauge is made in a variety of sizes to cover a complete range from 6 to 150 mm. Only five sizes of frames are used ; intermediate sizes are obtained by fitting one or other of a series of anvils which increase in length by steps of 5 mm. Any one particular gauge can be adjusted over a range of that amount by moving the anvil as mentioned above.

The working pressure between the anvils is of the order of 12 oz.

III. Depth Gauges

The simplest type of depth gauge for fairly shallow recesses is usually made from ground-flat stock, and takes the general form

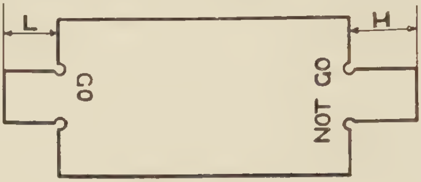


Fig. 23.

shown in Fig. 23. The lengths of the two tongues are made to the limiting dimensions for the depth of the hole.

Another form of limit depth gauge suitable for testing the depth of a comparatively deep cavity, such as the interior of a shell, is shown in Fig. 24. It consists of a rod A which passes through a hole

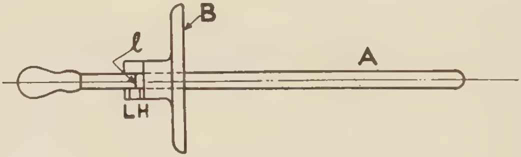


Fig. 24.

in a collar B, the under side of which is faced. A line *l* is scribed round the upper part of the rod, and when the gauge is in use the position of this line is noted with respect to two fixed lines L and H scribed on the collar, a portion of which is cut away for the purpose. The distance between the lines L and H is, of course, equal to the tolerance on the depth to be tested.

With fine tolerances, the use of lines does not lead to sufficient accuracy. More definite results are obtained by replacing them with surfaces. Fig. 25 shows at A and B alternative arrangements of three surfaces on the end of the plunger and the surrounding tube, whilst at C the plunger is shown extended to form a handle.

With such arrangements, the test is usually made by feeling the junction of the surfaces with the finger nail. When in doubt, however, a small straight-edge can be used to determine the relative heights of the surfaces.

The testing of depth gauges is a simple matter, and is usually

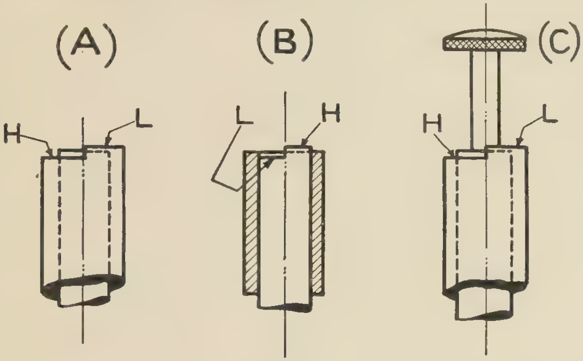


FIG. 25.

carried out with the help of a set of block or end gauges and a surface plate. Combinations of gauges are arranged to represent work on the two extreme limits and the gauge is tried upon them in turn.

IV. TAPER GAUGES

Limit taper gauges generally take the form illustrated in Fig. 26. The general fit of the work to the gauge gives some indication as to

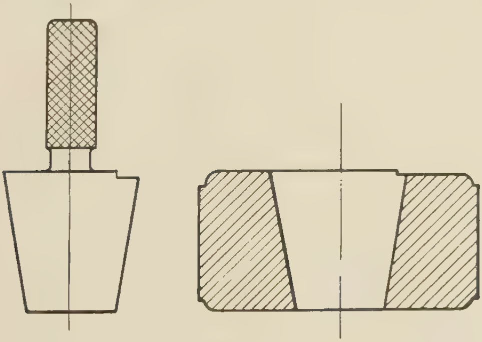


FIG. 26.

the accuracy of the angle of taper. This can be checked more definitely by the application of a marking material such as Prussian-blue paint. The diameters of the work are checked by noting its position, when fully assembled with the corresponding gauge, in relation to the stepped surfaces at the large end of the gauge. The difference between these represents the tolerance on the work.

When the limits on the work are particularly close, it sometimes becomes desirable to make a more rigorous test on the accuracy of the taper than can be obtained by the use of a full-length tapered gauge as explained above. The work can then be gauged towards each end in turn by supplementary gauges, as shown in Fig. 27.

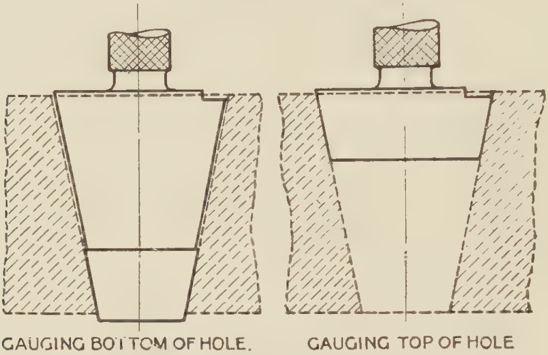


Fig. 27.

The gauge on the left, which deals with the smaller end of the cone, is cleared over its upper part, but is still provided at the top with the stepped surfaces denoting the limits.

Descriptions of other types of taper gauges will be found in Chapter V., which also contains details of various methods of testing these gauges.

V. Profile Gauges

Profile gauges can hardly be considered as limit gauges. Their purpose is to give some check on the general exterior shape or profile of work. The gauge is placed in contact with the surface to be tested, and the fit is generally judged by visual inspection against an illuminated background. Such a test clearly leaves much to the discretion of the inspector, but nevertheless usually suffices for the purpose.

A typical example of a profile gauge is shown in Fig. 28. This represents a set of templates for checking the profile of flat-bottom railway rails, or the rolls used in producing them. When used together, the two outside pieces constitute a " go " gauge for the rail.

A rather similar gauge used for checking the shape and general dimensions of a certain component of shrapnel shells is illustrated in Fig. 29. This acts as a "go" gauge for the work which must be small enough everywhere to pass through the hole in the plate. It need hardly be mentioned that to use a similar, but somewhat smaller, gauge for a "not go" test would be useless. Should the work happen to be above the lower limit across any one dimension it would not pass through the gauge, and would be liable to be accepted, no matter how small it happened to be in other parts. What is done in such cases is to apply a "not go" gauging test only on such important dimensions as the width and the height, and to inspect the general profile when the part is assembled with the "go" gauge.

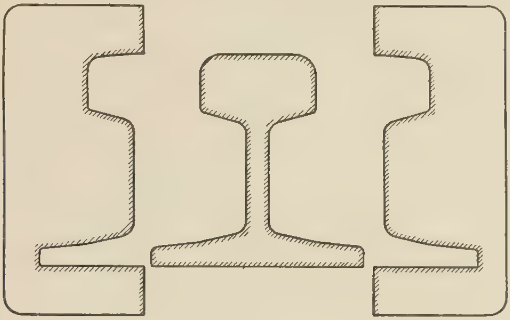


Fig. 28.

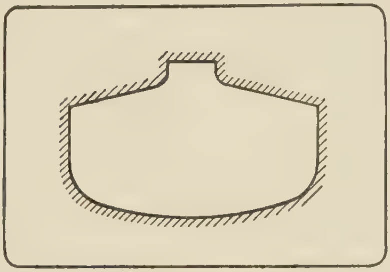


Fig. 29.

Various methods of testing profile gauges will be found in Chapter V. page 95 *et seq.*

VI. Position Gauges

This type of gauge is used for checking the relative locations of different parts of a piece of work or of an assembly of pieces. A simple example for checking the centring of two holes is shown in Fig. 30. It consists of two hardened steel pins *a* fixed parallel to each other in a block *b* at a distance apart equal to the nominal spacing of the holes in the work. In order to allow a certain tolerance on the spacing in the work, the two pins are made slightly smaller than the low diameter of the holes by an amount depending on the tolerance.

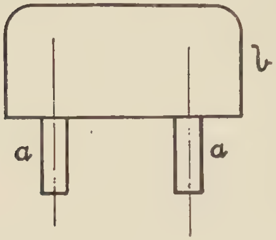


Fig. 30.

A "not go" plug gauge would be used in conjunction with this gauge to check the diameters of the holes on the high limit.

Fig. 31 shows, on the left, a position gauge for testing the location of the three holes A, B and C in the fuse body to the right. The body of the gauge, which is made of cast iron, is bored out to accommodate the conical surface of the fuse, and is provided with a hardened steel axial pin *a* which enters the hole A of the fuse. Two other pins, *b* and *c*, slide in hardened steel bushes fixed in the body of the gauge and in the correct positions to correspond with the holes in the fuse. For convenience in manufacture and in testing, the bushes are ground out to the same size, the pins *b* and *c* being reduced in diameter at the points to suit the diameters of the holes.

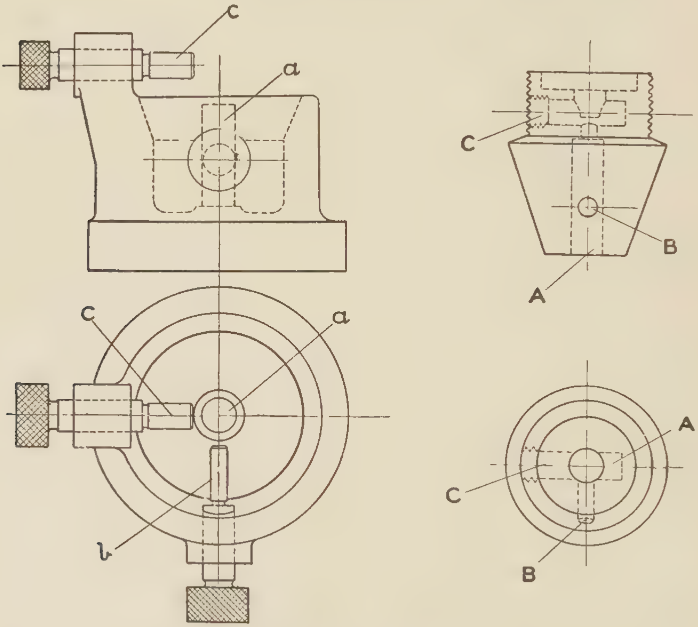


Fig. 31.

The operation of testing fuses with such a gauge is very simple. The fuse is dropped over the pin *a*, and is rotated until the holes B and C come in line with the corresponding pins. For the fuse to be satisfactory it should be possible to insert both pins into the fuse simultaneously.

As in the case of the simple pin gauge described above, the diameters of the gauge pins are made slightly smaller than the low diameters of the holes in the fuse, in order to allow tolerances on the relative positions of the various holes.

Methods of measuring position gauges are dealt with in Chapter V. p. 98.

ADDITIONAL REFERENCES FOR CHAPTER I

"Snap Gauge Design," *Machinery*, vol. 20, p. 7 (1922).
"Adjustable Limit Snap Gauge," *Amer. Mach.*, vol. 48, p. 469 (1918).
"Limit Snap Gauge," *Amer. Mach.*, vol. 46, p. 986 (1917).
"Spring of Gap Gauges," *Amer. Mach.*, vol. 62, p. 80 E (1925).
"The Use of Snap and Ring Gauges," *Amer. Mach.*, vol. 46, p. 253 (1917).
"Built-up Limit Snap Gauges," *Amer. Mach.*, vol. 47, p. 196 (1917).
"Built-up Snap Gauge," *Amer. Mach.*, vol. 61, p. 209 E (1925); vol. 62, p. 547 (1925).
"Improvements in Adjustable Limit Gauges," Patent No. 258,194 (1926).
"Snap Gauge Production," *Amer. Mach.*, vol. 47, p. 49 E (1917).
"New Adjustable Caliper Gauge," *Amer. Mach.*, vol. 66, p. 289 E (1927).
"Adjustable Snap Gauge," A. J. C. Brookes, Patent Spec. 237,163 (1925).
"Gap Limit Gauges," J. Barnden, *Amer. Mach.*, vol. 66, p. 316 E (1927).
"Setting Adjustable Gap Gauges," W. Groocock, *Amer. Mach.*, vol. 62, p. 18 E (1925).
"The S.A.S. Adjustable Limit Snap Gauge," *Amer. Mach.*, vol. 47, p. 569 (1917).
"Adjustable Limit Plug Gauge," *Machinery*, vol. 23, p. 737 (1924).
"The Making of Plug and Ring Gauges," *Amer. Mach.*, vol. 48, p. 191 (1918).
"Plug Gauges," *Amer. Mach.*, vol. 46, p. 1136 (1917).
"Limit Plug Gauges," *Amer. Mach.*, vol. 46, p. 242 E (1917).
"Adjustable Limit Gauge," *Machinery*, vol. 19, p. 534 (1922).
"Renewable-end Plug Gauges," *Eng.*, vol. 110, p. 210 (1920).
"Making Built-up Gauges," G. Haessler, *Amer. Mach.*, vol. 61, p. 354 (1924).
"Limit Gauges," *Eng.*, vol. 110, p. 643 (1920).
"A Special Depth Gauge," *Amer. Mach.*, vol. 48, p. 463 (1918).
"Gauge for Depth of Recesses," *Amer. Mach.*, vol. 48, p. 291 (1918).
"The Use of Feeler Gauges," *Amer. Mach.*, vol. 47, p. 420 (1917).
"Feeler Gauges for Recesses," *Amer. Mach.*, vol. 48, p. 228 (1918).
"Gauge Wear," A. J. C. Brookes, *Amer. Mach.*, vol. 61, p. 209 E (1925).
"Accurate Control in Interchangeable Manufacture," *Machinery*, vol. 28, p. 361 (1926).
"Precision Gauge Manufacture," *The Engineer*, vol. 131, p. 312 (1921).
"The Manufacture of Length Gauges," *Machinery*, vol. 19, p. 640 (1922).
"Gauge Lapping," *Machinery*, vol. 19, p. 540, 1922.
"Manufacture of Wickman Gauges," *Machinery*, vol. 33, pp. 257, 397 (1928).
Gauge Design and Gauge Making, E. Oberg and F. D. Jones (Machinery-Pub. Co., 1920).
Gauges, Gauging and Inspection, D. T. Hamilton (Machinery-Pub. Co., 1918).

(See also additional References to Chap. I. Vol. I. p. 11.)

CHAPTER II

MICROMETERS

THE micrometer is the commonest form of measuring instrument capable of giving direct end-measurements to the order of 0·001 inch. It is perhaps not generally known that one of the earliest micrometers was made by James Watt over a century ago, and is preserved in the Science Museum at South Kensington. A photograph of the instrument, which is reproduced by courtesy of the Director of the Museum, is shown in Fig. 32.

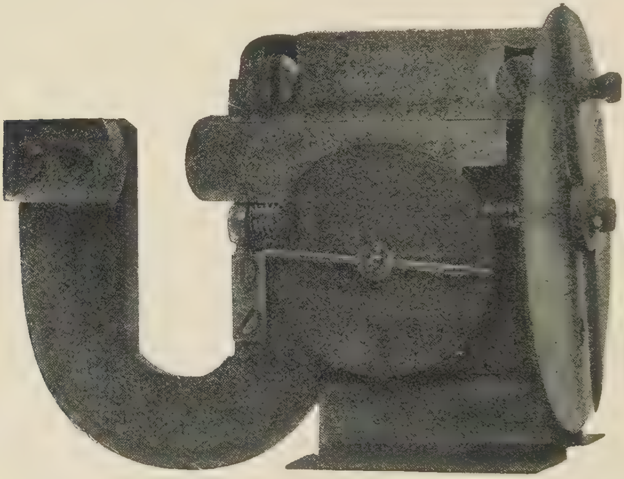


FIG. 32.

The brass, horse-shoe body has on one side a fixed anvil of iron or steel, and on the other a second anvil fitting in a dove-tail slide. This anvil can be moved to and fro by means of a screw working in a rack cut along its lower edge. The outer end of the screw, which has a pitch of about 19 T.P.I., is furnished with a thin brass dial about 4 inches diameter, having 51 divisions on the face, each of which is apparently intended to represent 0·001 inch. Complete revolutions of the screw are recorded by a pointer which moves over a smaller dial having 19 divisions on its face, the index being attached to a worm wheel which meshes with the screw. The faces of the anvils are rounded, and the maximum opening is about an inch.

Subsequent developments of the micrometer took place in France, where in 1848 an instrument was produced by Palmer, taking the form shown in Fig. 33. The only essential difference between this early form and the modern type of micrometer is in the spindle, the screw of which was exposed. The actual manufacture of micrometers was taken up in America by Messrs. Brown and Sharpe in 1867, and Fig. 34 A shows one of their early types of about that period. It was not until about 1885 that the present practice of protecting the screw from dust and mechanical injury by concealing it within the thimble was started in the United States by M. M. Barnes. The Brown and Sharpe instrument of 1885, shown in Fig. 34 B, incorporated this improvement, and differs very little in external form from modern practice, a typical example of which, as made by the Starrett Company, is shown in Fig. 35.

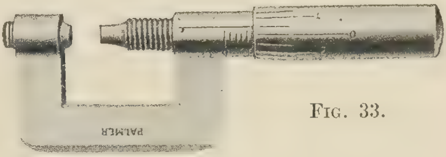


FIG. 33.

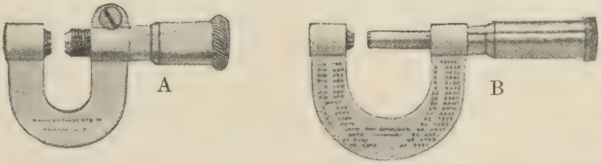


FIG. 34.

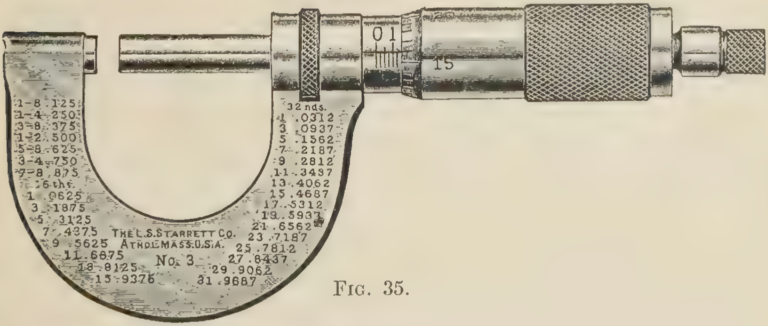


FIG. 35.

General Construction.

The general construction of a micrometer can be seen from the sectional arrangement of a Brown and Sharpe instrument, Fig. 36. The U-shaped frame has a fixed anvil at one side, whilst the other is extended in the form of a tube, or barrel, which acts as a support for the micrometer nut. The measuring spindle is screwed for about half its length with an accurately cut, fine-pitch thread which engages freely with the nut in the frame. The spindle obtains additional support over its parallel portion in a well-fitted hole in the frame. The outer end of the spindle carries a sleeve, or thimble, which can turn freely round the outside of the barrel. The bevelled edge of this thimble is graduated, and the readings are taken against a longitudinal datum line on the barrel. Complete revolutions of the thimble can be recorded by noting the position of the bevelled edge against a series of short graduations on the barrel, spaced at intervals equal to the pitch of the screw.

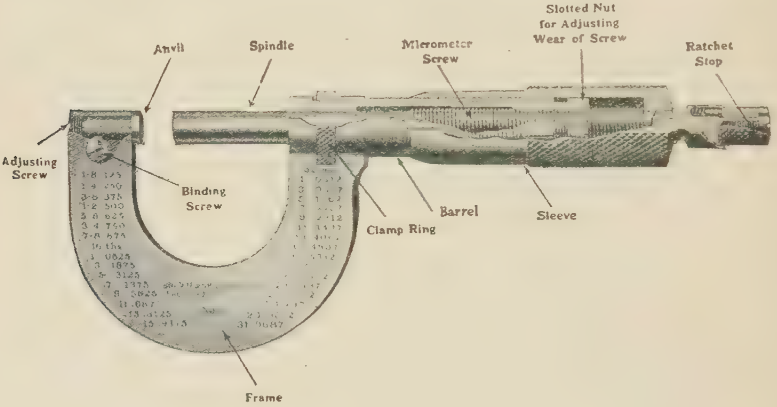


FIG. 36.

The measuring faces of the anvil and micrometer spindle are hardened, and are usually about $\frac{1}{4}$ or $\frac{5}{16}$ inch diameter. Unless intended for special purposes, they are both flat, and, in order to maintain their parallelism for any position of the spindle, the face of the latter has to be accurately square to its axis.

Micrometers are ordinarily constructed to measure either in inch or metric units. In the former case it has become an established practice to use a micrometer screw having 40 threads per inch and to graduate the thimble with 25 divisions, each of which, therefore, represents 0·001 inch in the longitudinal position of the spindle. This type of graduation is shown clearly in Fig. 35. The available run of the micrometer screw is usually an inch.

When designed to read in metric units, the screw usually has a pitch of 0·5 mm., and 50 divisions are engraved round the thimble, each representing 0·01 mm. This type of graduation is shown in Fig. 37. The divisions along the barrel are spaced at intervals of 0·5 mm. For the sake of clearness, those representing the full millimetres are marked on one side of the datum line on the barrel and the half-millimetre lines on the other side.

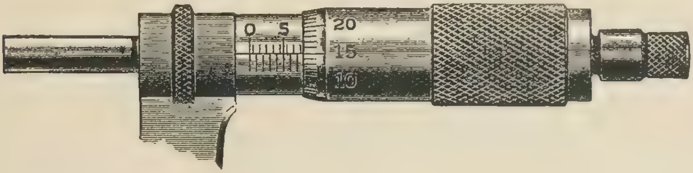


Fig. 37.

Ratchet Stop and Friction Drive.

When measuring an object with a micrometer, the spindle is advanced by rotating the thimble between thumb and fingers until contact is felt between the object and the measuring faces. Experience has shown, however, that this method of setting by " feel " is liable to give rise to a variation of as much as 0·0002 or even 0·0003 inch in the reading when the same micrometer is used by different persons. This is due to differences in the pressure exerted upon the object between the faces.

The effect of this difference can be eliminated if the micrometer be used only as a comparator ; a setting is first taken upon a gauge of known size, and the reading is compared with that obtained subsequently upon the object to be measured. For a given operator the effect of pressure will be alike in the two cases. Incidentally, it is an advantage to use either a plug gauge or one with flat ends, according to the form of the object : this eliminates the effect of any errors in the flatness or parallelism of the faces, and permits the same " feel " to be obtained in the two settings. The size of the gauge should also be as close as possible to that of the object. The difference between the readings will then be small, and any errors in the run of the micrometer screw will affect the comparison to only a negligible degree.

Consistency of touch between different operators can be ensured by the addition to the micrometer of a device usually known as a ratchet stop or friction drive. The thimble is rotated by means of a small knurled head which is to be seen to the right hand of Figs. 35, 36 and 37. When the end of the spindle comes in contact with the object between the faces, and a certain pressure becomes set up, the driving device slips. The personal touch of the operator is thereby eliminated.

There are various constructions of this small driving head. That adopted by Brown and Sharpe consists of a small sleeve A, Fig. 38, having on its left-hand end a series of teeth which engage with the spring-controlled pawl B. The shape of the teeth and the tip of the pawl are such that the engagement between them is quite definite in the action of unscrewing the micrometer spindle, but in the opposite direction any undue resistance to the advancement of the spindle causes the pawl to come out of engagement, and the small sleeve continues to turn without driving the screw. The Starrett device is very similar, the pawl being replaced by a small toothed collar, as shown in Fig. 39.

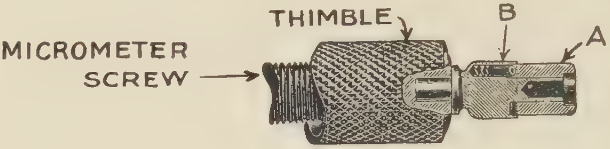


FIG. 38.

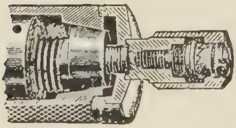


FIG. 39.

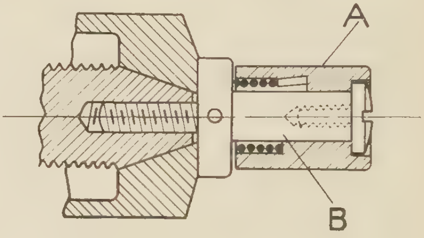


FIG. 40.

The type of driving head used by Johansson possesses the advantage of providing a smoother and more pleasing action when slipping occurs. Connection between the driving sleeve A (Fig. 40) and the pin B, which is screwed to the end of the micrometer spindle, is by means of a spiral spring, one end of which is attached to the sleeve, whilst the other presses against the face of the collar on B. When advancing the micrometer spindle, rotation of the sleeve A drives the screw through the friction of the spring against the face of the collar. Slipping occurs, however, as soon as any resistance to the screw is experienced. The action becomes quite positive in the reverse direction, since the spring tends to uncoil and becomes jammed in the space between the sleeve and the pin B.

Adjustments for Wear.

In all the better class makes of micrometers there is provision for readjusting the instrument as wear takes place between the working parts. Means are provided for eliminating backlash between the micrometer screw and its nut, and for resetting the zero, should it be necessary to relap the measuring faces.

One method of adjusting the fit of the screw and nut is shown in Fig. 36, p. 26. The nut projects for about half its length beyond the barrel; this projecting portion is split longitudinally in several places, and has a tapered screw on its outer surface. By screwing an auxiliary nut up or down this thread, the fit of the micrometer screw can be readily adjusted. The zero adjustment on this instrument is made by a finely-threaded screw which controls the position of the anvil. When set, the anvil can be locked in place under the conical head of the binding screw shown.

The same figure also shows the usual arrangement for locking the micrometer spindle when it is desired to use the micrometer as a fixed calliper. It consists of a knurled ring A (Fig. 41) fitting round a split collar B, through which the plain portion of the spindle passes. The collar has an angular recess containing a small steel pin C. On slightly turning the ring A, the pin becomes jammed between the ring and the recess. This closes in the collar and grips the spindle. A slight turn of the ring in the opposite direction is sufficient to free the spindle.

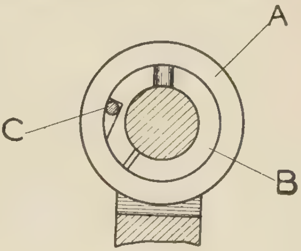


Fig. 41.

The Slocomb micrometer has a special method of adjustment for wear. The main nut A (Fig. 42) has 40 T.P.I. as usual, but, instead of being pressed into the barrel B, is screwed into it, the thread having a pitch of 32 T.P.I. By screwing the nut into or out of the barrel a differential screw adjustment of the zero is obtained; one complete turn of the nut corresponds to an axial movement of the spindle of 0·00625 inch. In addition to this adjustment, backlash of the screw is taken up by the use of an auxiliary nut C, which is prevented from rotating with respect to the main nut by a series of interlocking teeth on their adjacent faces. A light helical spring is enclosed in a recess between the two nuts, and the pressure of this spring maintains steady contact between the working flanks of the threads on the spindle and in the nut.

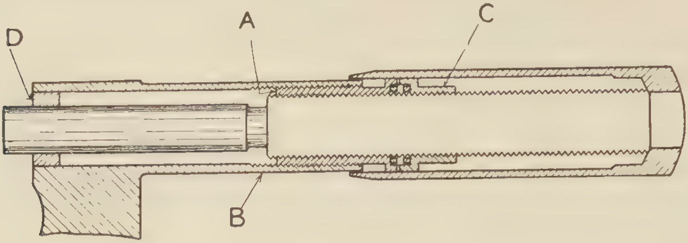


Fig. 42.

This method of preventing end-play between the micrometer spindle and its nut has the advantage of always utilizing the full working length of the nut, whereas, when adjustment is made by springing in the end of the nut, contact between the two screws is confined rather to the small end of the nut.

Another special feature of this micrometer is the hardened guiding bush D for the spindle. This is pressed into the end of the barrel, and can be replaced if it becomes worn. The friction drive is similar in principle to that used on the Johansson micrometers and is described on p. 28.

In the Starrett micrometer the zero adjustment is made by turning the barrel with respect to the frame of the instrument. For this purpose, the barrel is made in the form of a sleeve which fits fairly tightly over the housing for the nut.

The zero adjustment for the Johansson micrometer is made by turning the graduated thimble relative to the spindle. The thimble can be freed from the spindle by slightly slackening the pin B, Fig. 40, p. 28, and, with the measuring faces in contact, the zero line on the thimble is set to coincide with the datum line. The pin is then tightened.

Hardened Micrometer Screws.

Johansson micrometers are worthy of special note, in so much as the first quality instruments of this make have hardened and ground micrometer screws running in bronze nuts. This combination results in an exceptionally smooth and even action, and, according to the makers, provides greater accuracy and a longer useful life. The accuracy of the screw is guaranteed to ±0·00004 inch.

General Accuracy of Micrometers.

The general experience of the author in testing micrometers of various makes is that the better class instruments can be relied on to give measurements accurate to within ±0·0001 inch. This refers to micrometers having a range up to 1 inch with the zero correctly adjusted. Even the cheaper makes seldom have errors exceeding 0·00025 inch, when new.

Inaccuracies are to be found more frequently in the measuring faces due to lack of flatness, parallelism and squareness of the face of the spindle to its axis. It may happen that the faces are truly parallel when the instrument is set to zero, but error arises when the spindle is rotated through half a turn due to lack of squareness of the revolving face.

Devices for Increasing Accuracy of Reading.

(i) *Vernier.*—The ordinary micrometer measuring in inch units is usually graduated to read direct to 0·001 inch; if the next decimal place is required, it has to be obtained by estimation of the subdivision. To enable the reading to be made with greater certainty, micrometers can be obtained with the addition of a vernier. This usually takes the form of eleven equally-spaced lines engraved along the barrel parallel to the axis of the screw, as shown in Fig. 43. The overall width of the ten spaces of the vernier is the same as that occupied by nine divisions on the rim of the thimble. The reading is obtained, as usual, to three decimal places with reference to the datum line F. Thus, the reading as shown at B is exactly 0·250. At C the reading is slightly larger than this by a fraction of 0·001. This fraction is ascertained by reference to the vernier where coincidence is seen to occur at the line 7. The complete reading is therefore 0·2507 inch.

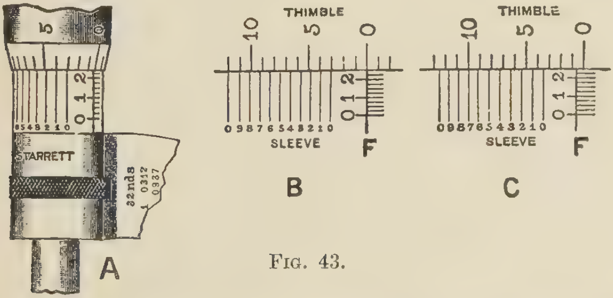


Fig. 43.

(ii) *Special Fittings.*—The makers of the Slocomb micrometer provide a special fitting for their micrometers which can be used when measuring a large number of parts of closely the same size. It consists of a graduated sector of aluminium, Fig. 44, which can be clamped to the thimble, and a corresponding part attached to the barrel of the micrometer bearing a fiducial line. The periphery of the sector has a scale with a range of ±0·002 inch and is graduated to read to 0·0001 inch. The diameter of the sector is such that the 0·001-inch divisions are spaced $\frac{3}{16}$ inch apart, as compared with 0·06 inch on the thimble itself. In using this device, the position of the fiducial line has to be set with a standard piece of known size placed between the jaws.

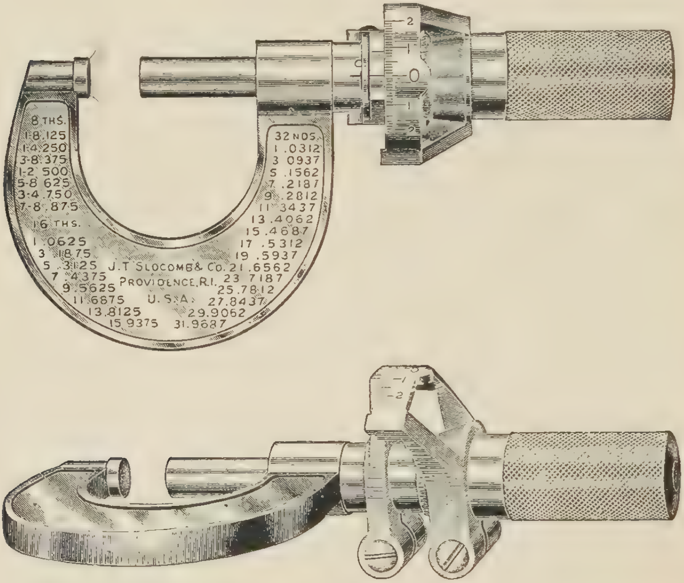


FIG. 44.

A special type of Brown and Sharpe micrometer for giving measurements up to half an inch, direct to four decimal places, is shown in Fig. 45. This differs from an ordinary micrometer in having a screw with 50 T.P.I. and an enlarged thimble with a diameter of 1¼ inch. The latter has 200 divisions, each representing 0·0001 inch. In using this instrument, care has to be taken to bring the screw up very gently, otherwise the inertia of the enlarged thimble is likely to set up an abnormal pressure between the jaws, and result in an appreciably small reading. The same type of micrometer is made to measure in metric units ; a small division on the thimble then represents 0·005 mm.

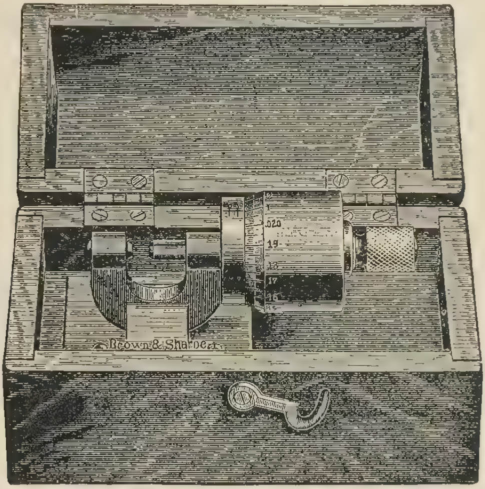


Fig. 45.

(iii) *Indicating Anvil.*—Another interesting type of micrometer capable of giving measurements direct to 0·0001 inch is one made by Messrs. Zeiss, an example of which is shown in Fig. 46. The anvil is movable, and is connected to a system of magnifying levers so that its movements are indicated about 600 times by a pointer passing over a scale. The latter is graduated to read to either 0·0001 inch or 0·002 mm., and has a range of ±0·001 inch or ±0·02 mm. The

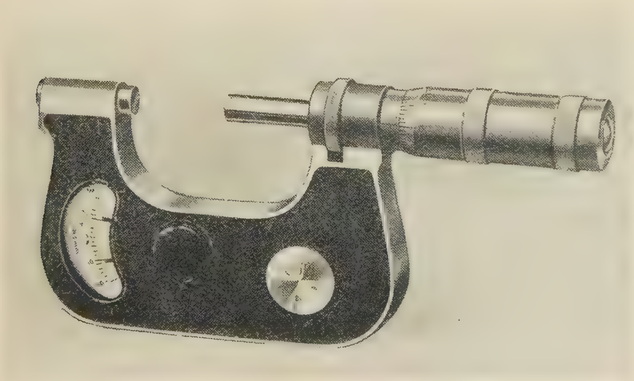


Fig. 46.

instrument is adjusted so that the pointer is on the central zero line of the scale when the measuring faces are in contact and the thimble is at zero. To measure an object, the thimble is brought exactly to the nearest line, and the indicator then registers the departure of the size of the object from that reading, either plus or minus.

When testing a number of repetition parts, two auxiliary pointers can be set to the specified limits, and, having set the spindle to the appropriate reading and locked it in position, the parts can be rapidly gauged by passing them in succession between the jaws.

Direct Reading Micrometer.

In order to save the mental calculation required in reading an ordinary micrometer, there are certain types in which the first three decimal places are automatically recorded by a counting mechanism. A Slocomb micrometer of this type is shown in Fig. 47. The lines on the barrel indicating the complete revolutions are omitted, as is also the numbering on the thimble. The screw has a pitch of 50 T.P.I., and there are 20 divisions on the thimble. The only function of these graduations is to obtain an estimate of the ten-thousandth figure which has to be added to the recorded part of the reading.

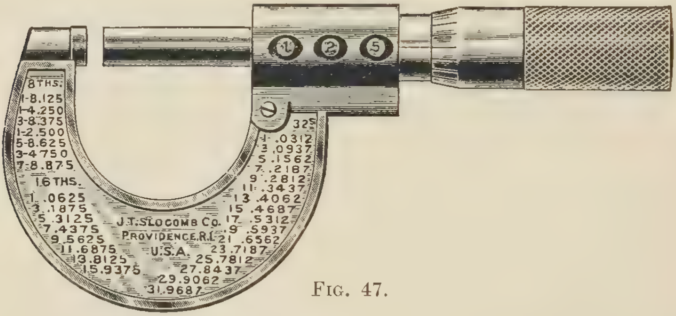


FIG. 47.

Combined Metric and Inch Micrometer.

A rather novel type of micrometer, known as the " Metr-Inch ", which gives equivalent measurements in both inch and metric units, is shown in Fig. 48. Its screw has 50 T.P.I., and there are 20 divisions, each representing 0·001 inch, round the extreme edge of the thimble. These divisions, together with the fiftieth of an inch scale along the barrel, enable measurements to be made as usual in inch units. The method of indicating in metric units is based upon the closely approximate relation, 1 inch equals 25·4 mm. Since one complete turn of the thimble corresponds to 0·02 inch (0·508 mm.), slightly less than a turn would be required to give a traverse of 0·5 mm. to the spindle. A helical datum line is therefore engraved round the barrel, having a pitch to correspond with the difference of 0·008 mm. per revolution of the thimble. This helical line is used as the datum line for a scale of 50 divisions engraved round the inner edge of the thimble, each division representing 0·01 mm., as in an ordinary metric micrometer. The arrangement of the two scales on the thimble and those on the barrel are shown more clearly in the enlarged diagram of Fig. 48.

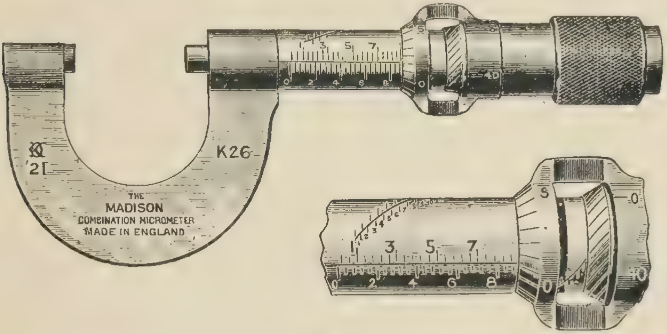


Fig. 48.

Micrometers with Special Measuring Faces.

For all ordinary purposes micrometers are fitted with flat, parallel, measuring faces. Other types of faces are used, however, to suit special requirements. An example of a type of anvil used when measuring the walls of tubes, or the distance of a hole from the edge of a piece, is shown in Fig. 49. The anvil is cylindrical, and has a diameter of $\frac{3}{8}$ inch.

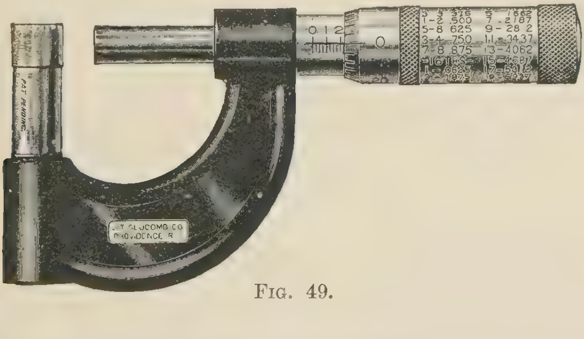


Fig. 49.

The contact faces of micrometers for screw thread measurements take the form shown in Fig. 50. The end of the micrometer spindle A is ground conical, and is suitably rounded off at the point; the anvil B has an internal vee which fits over the thread of the screw to be measured, and can rotate about its axis so as to allow the vee to accommodate itself to the rake angle of the thread. The angles of the cone and the vee are made equal to the theoretical angle of the screw thread. When the spindle of the micrometer is screwed up to bring its conical point into the vee, the reading is then zero; consequently, when the contact points are set so that a screw will just pass between them, as in Fig. 50, the reading gives the effective diameter of the screw directly.*

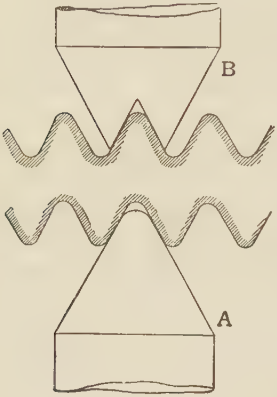


Fig. 50.

Taking a micrometer with a particular pair of contact faces, it is generally possible to use it over a limited range of consecutive pitches of threads, at the same time maintaining contact on the flanks of the threads only. The limit is reached in one direction when the points of the anvil foul the roots, and in the other when the conical point barely enters the space between the threads. For this reason it is necessary to have a number of micrometers, each with different size contact faces, in order to cover a whole range of pitches.

Micrometer Heads.

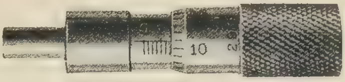
The measuring heads incorporated in ordinary micrometers are also made as separate units without the bow-frame. As such they can be put to many uses when attached to machine tools, jigs and measuring devices. Their internal structure is the same as in a micrometer. Two types, of Brown and Sharpe manufacture, having ranges of half-inch and one inch respectively, are shown in Fig. 51. The cylindrical stems upon which they are held are made to a standard diameter of $\frac{3}{8}$ inch in both cases.

Enlarged Dial Fittings.

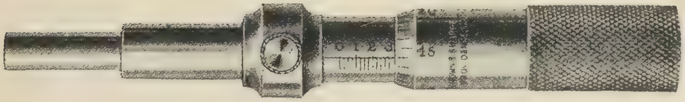
When applied to certain types of measuring instruments, it is sometimes desirable to be able to read a micrometer head more accurately than is possible by the use of the graduations on the thimble. Fig. 52 shows a form of enlarged barrel and dial as designed at the National Physical Laboratory. The original thimble of the micrometer head is cut down to a short length A, upon which

---

* Errors in the angle of the thread have a marked influence upon the measurement. For further information, see Vol. III.



1-2″ Micrometer Head



1″ Micrometer Head

Fig. 51.

the larger thimble B is fitted. Similarly, a larger barrel C, 1½-inch diameter, is placed over the existing one. The barrel is graduated as usual with a series of lines indicating the complete revolutions, whilst the bevelled edge of the thimble has the twenty-five thousandth of an inch divisions subdivided to read to 0·0002 inch.

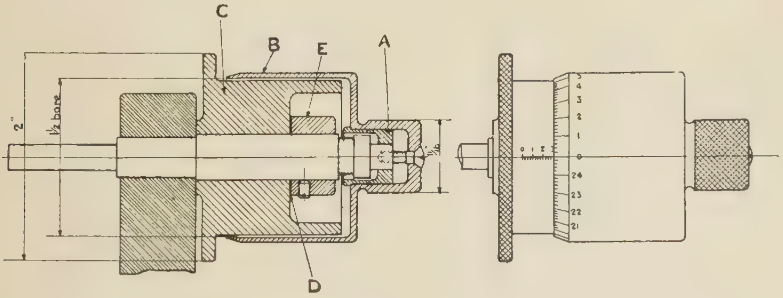


Fig. 52.

The enlarged barrel can be turned on its seating for purposes of zero adjustment, and, having been set, is held in position by the collar E and the pressure of the spring-washer D. The enlarged thimble and barrel are constructed of aluminium ; in addition, the thimble is made as light as possible to prevent its inertia interfering with the “ feel ” of the micrometer.

Micrometer Head with Differential Screw.

The accuracy of the reading of a micrometer can be considerably increased by using the principle of differential screws. This scheme is illustrated in Fig. 53, which shows a micrometer head designed for a special purpose at the National Physical Laboratory. The micrometer spindle A has two threads cut upon it, the larger one having 20 and the smaller 25 threads per inch, both being right-handed. The former runs in a fixed nut at the right-hand end of the barrel B, whilst the finer-thread screw passes through a nut fixed in the hollow plunger C, the exposed end of which forms the measuring face of the instrument. The plunger is guided at each end inside the barrel, and is prevented from rotating by a small key working in a longitudinal slot. The spring shown maintains satisfactory contact between the micrometer screw and the two internal threads.

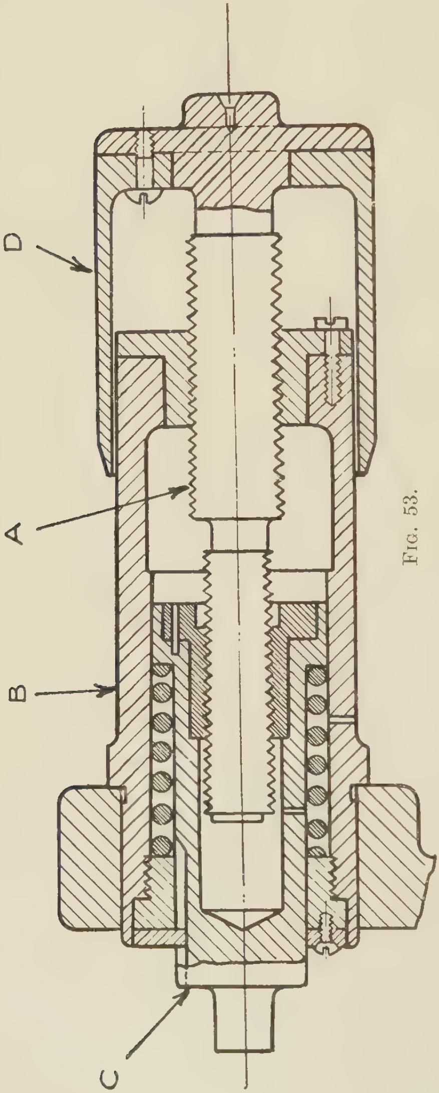


Fig. 53.

On revolving the micrometer spindle through one turn, it advances to the left by $\frac{1}{20}$th inch, and, at the same time, the plunger moves $\frac{1}{25}$th inch to the right with respect to the spindle. The nett movement of the plunger is therefore $(\frac{1}{20} - \frac{1}{25})$ inch, *i.e.* 0·01 inch to the left. The edge of the thimble D, attached to the screw, is graduated with 100 divisions, each representing 0·0001 inch, the distance separating adjacent lines being about 0·04 inch. The magnification is therefore of the order of 400, as compared with about 60 for an ordinary micrometer having a 40 T.P.I. screw and a thimble about $\frac{1}{2}$-inch diameter.

It is to be noted that a travel of 1 inch of the micrometer screw produces a movement of the plunger of only 0·2 inch. The total range of such an instrument is therefore limited unless the micrometer screws are made proportionately long.

Larger Types of Micrometers.

The micrometers described on the previous pages are suitable for measurements up to 1 inch or 25 mm. only. Those used for larger measurements differ only in the size of the bow-frame. For example, a range of from 2 to 3 inches would be covered by an instrument as in Fig. 54. The 2-inch end gauge shown is used for checking the zero.

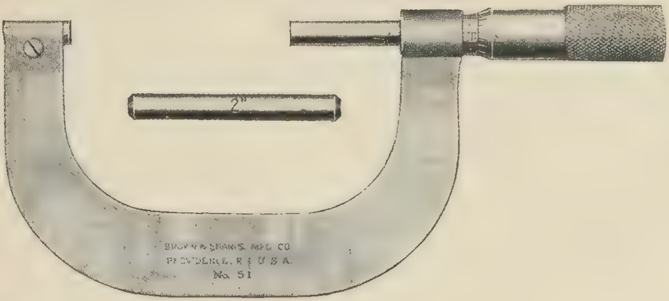


Fig. 54.

A complete set of micrometers for making any measurement up to 12 inches is shown in Fig. 55. The frames of the larger sizes of micrometers have to be made as light as possible for ease in manipulation, and, in order to obtain rigidity, an H-form of section is generally adopted.

The twelve end gauges used for checking the terminal readings are to be seen in the tray at the base of the stand. Such gauges usually have spherical ends, the radius of curvature being equal to half the length of the rod. Their absolute lengths are generally accurate to ±0·0001 inch.

It can be readily understood that measurements cannot be made as accurately with the larger sizes of micrometers as with those of more limited capacity. The difficulty of manipulation increases with the size and weight of the micrometer; the lack of definite "feel" also becomes more and more pronounced on account of elastic springing of the frame. The latter trouble has been overcome to a large extent by Messrs. Zeiss by the use of an adjustable indicating anvil as in Fig. 56. This is held in the micrometer frame in place of the usual solid anvil. It contains a spring-controlled plunger, the rear end of which actuates a magnifying system of geared levers, terminating in a pointer which passes over a scale graduated to read to either 0·001 inch or 0·01 mm., and having 5 divisions on each side of the zero. Having set the position of the indicator in the frame by means of an end gauge, subsequent

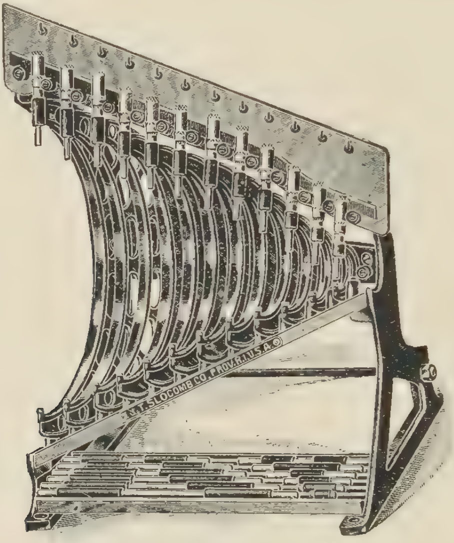

J.T. SLOCOMB CO. PROV. R.I. U.S.A.

Fig. 55.

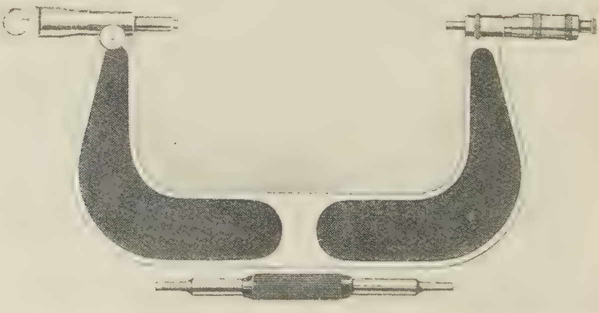


Fig. 56.

measurements are made by bringing the pointer to the central zero mark on each occasion, thus ensuring constancy of pressure. If desired, small differences between pieces can be measured on the scale of the indicator after clamping the micrometer head. The shank of the indicator is sufficiently long to enable a single micrometer frame to be used over a range of 2 inches.

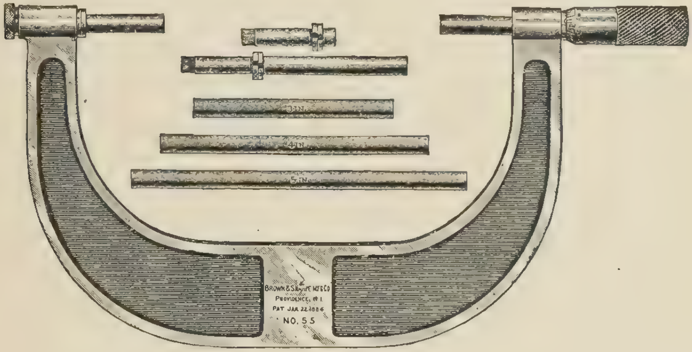

3 IN.
4 IN.
5 IN.
BROWN & SHARPE MFG CO
PROVIDENCE, R.I.
PAT JAN 22 1884
NO. 55

Fig. 57.

By having a series of anvils, it is possible to cover a range of several inches with a single micrometer. The set shown in Fig. 57, for example, covers a range from 3 to 6 inches. Three anvils and the same number of setting bars are provided. It should be mentioned, however, that measurements towards the lower end of the range cannot be made with the same delicacy of touch as when using a micrometer with a frame suitable for the particular size concerned. On the other hand, the saving of cost as compared with a number of separate micrometers to cover the same range is, of course, appreciable.

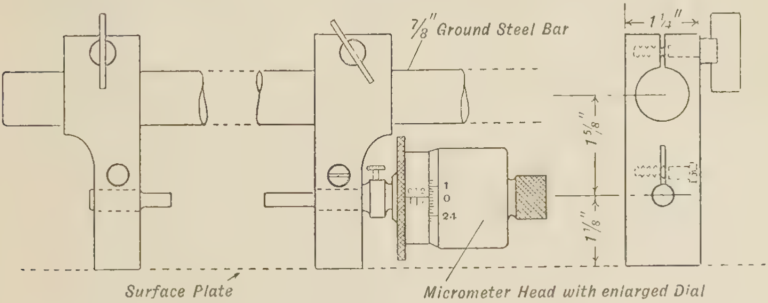


Fig. 58.

A bar-micrometer of the form shown in Fig. 58 is very convenient for carrying out measurements on a surface plate. The anvil and micrometer head are held in blocks which can be clamped at any position along a stout, steel bar accurately ground from end to end. The length of the bar is made to suit the range of measurement which it is desired to cover. When in use, the sliding blocks rest upon the surface plate. The zero setting has to be made, of course, upon a suitable end gauge.

" Built-up " Micrometers.

One of the many workshop applications of block gauges is their use as distance pieces for building up a micrometer, as illustrated in Fig. 59—an arrangement due to Johansson. Two hardened steel arms with ground and lapped faces are held in the familiar type of Johansson clamp with a block gauge wrung between them. One of the arms carries a micrometer head of the usual design, so arranged that when the reading is at the outer extremity of the range the measuring face of the spindle is flush with the lapped surface of the arm. It is then a simple matter to obtain the size of an object from the micrometer reading and the size of the gauge used as the

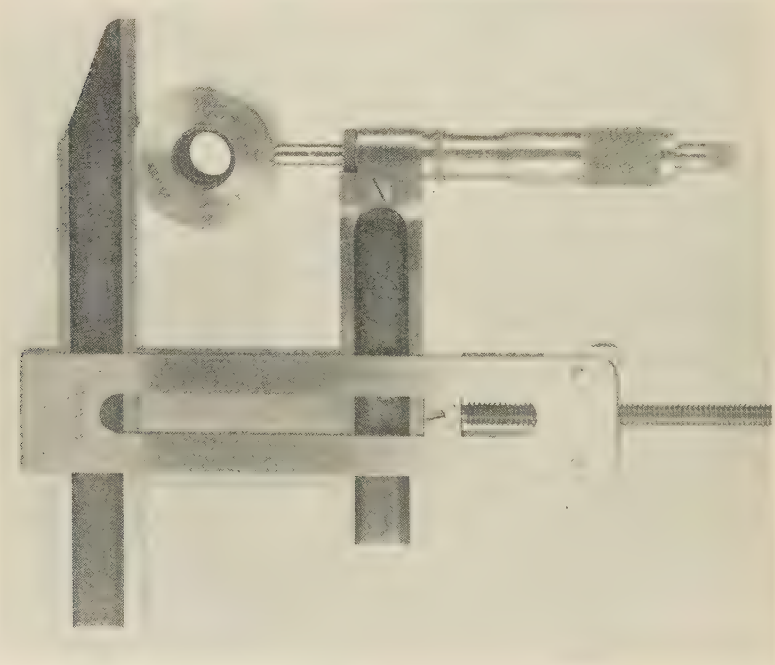


Fig. 59.

separator. The range of the instrument can be extended up to about 2 metres by using specially long gauges and a suitable clamp.

Another form of adjustable micrometer, suitable more especially for fairly long measurements, is that designed by The Pitter Gauge and Precision Tool Company, Woolwich. It comprises a pair of light, but rigid, end brackets C (Fig. 60), one fitted with a solid anvil and the other with a robust type of micrometer head having a range of about an inch. Each bracket has screwed into it two hardened steel sockets. After fixing these in position each bracket is placed upon a large lapping plate, and the outer faces F of the sockets are lapped simultaneously with the face of the anvil or of the micrometer, as the case may be. During this operation on the micrometer bracket, the reading of the head is set carefully to the 1-inch end of its travel.

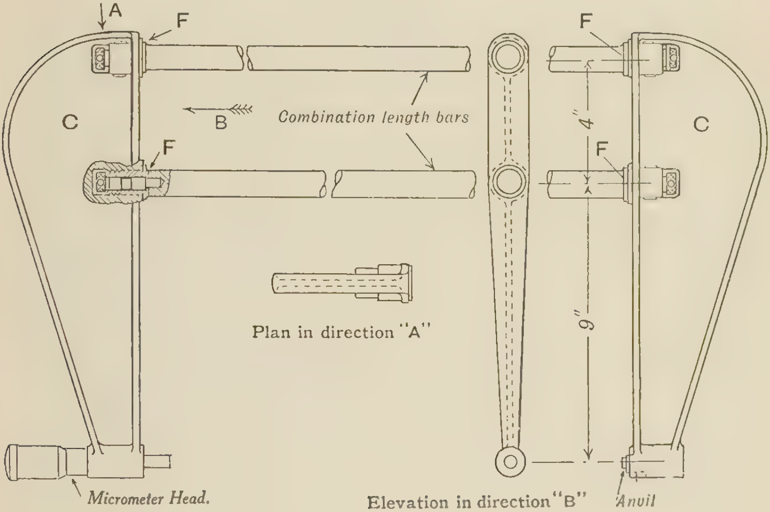


FIG. 60.

The distance pieces used to separate the end brackets consist of two of the firm's well-known type of workshop end bars.* The faces of these end bars are hardened and lapped so that they can be wrung on to the faces of the sockets, the joints being made secure by means of screws passing through the sockets and entering tapped holes in the ends of the bars. Having once been set up with a pair of equal size end bars, the micrometer is quite rigid, and can be used for direct measurements without reference to any other standard.

---

* For full description, see Vol. I. p. 108.

It is of interest to note that the end bars are ordinarily supplied in sets of twelve, comprising the following lengths: 31, 23, 15, 8, 7, 6, 5, 4, 3, 2, (2) 1 inches. With two such sets it is possible to arrange the micrometer to give any measurement up to 39 inches. It should be pointed out that when it is required to separate the end brackets by such a distance as, say, 19 inches, for which a single gauge is not provided, the length is made up by wringing together two of the gauges from the set, such as the 15- and 4-inch sizes. In addition to being wrung together, such gauges are prevented from breaking apart by a stud screwed partly into the end of each.

If, as the result of wear or damage, either of the measuring faces or the faces of the socket become defective, it is a simple matter to restore them to the original state by relapping in the manner described above.

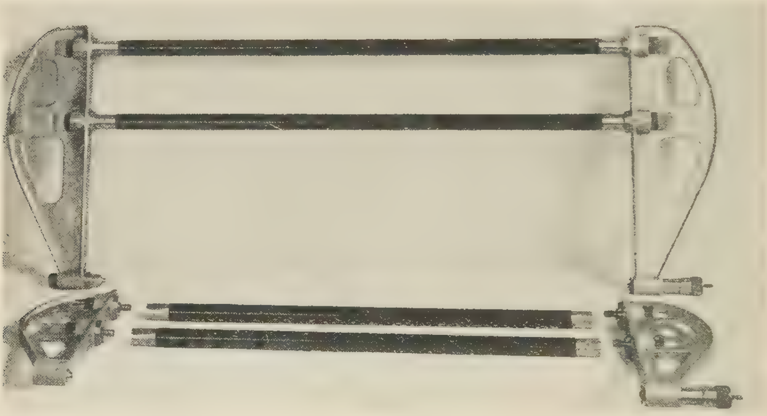


FIG. 61.

A photograph of a micrometer of this type in its complete form, and of another separated into its main components, is shown in Fig. 61.

TESTS OF MICROMETERS

It may be of interest to give some account of the usual methods adopted for testing micrometers.

Preliminary Tests.

The examination of a micrometer should begin with a superficial inspection covering the following points:

(i) General workmanship.

(ii) Smoothness of running of micrometer screw throughout its traverse.

(iii) End-play in micrometer screw.

(iv) Hardness of measuring faces.

(v) Clearness of graduations and their correct numbering.

Accuracy of Measuring Faces.

Following this, attention should be concentrated upon the truth of the measuring faces. These should be well polished, flat to within 0·0001 inch and parallel for all positions of the micrometer spindle. The flatness is tested most readily with the aid of a small piece of optically-flat glass, using the phenomenon of optical interference.* This test gives not only a direct indication as to the quality of flatness, but also reveals instantly the presence of any burrs.

In the case of a 0–1-inch micrometer, the parallelism of the faces can be tested by measuring a steel ball at various positions towards the periphery of the faces. It sometimes happens that, owing to lack of squareness of the face of the spindle with the axis of rotation, the degree of parallelism varies as the spindle is turned. It is therefore desirable to make the test with a number of balls whose sizes are such as to bring the spindle to different positions in the revolution. A suitable series of balls is $\frac{1}{4}$ (0·250), $\frac{9}{32}$ (0·28125), $\frac{5}{16}$ (0·3125) and $\frac{11}{32}$ (0·34375) inch. For a metric micrometer the following series may be used: $\frac{11}{32}$ $\frac{25}{64}$, $\frac{13}{32}$, $\frac{7}{16}$ and $\frac{29}{64}$ inch, the metric equivalents of which are: 8·731, 9·922, 10·318, 11·113 and 11·509 mm. In a good micrometer the variation in the reading obtained on any of the balls, when placed at different positions between the faces, should not exceed 0·0001 inch.

This form of test for parallelism of faces is still applicable for larger sizes of micrometers if ball-ended rods are used for the measurements. These rods can be made most conveniently by soldering $\frac{1}{4}$-inch steel balls to the ends of a suitable length of steel rod, as in Fig. 62. If desired, four or five such test rods of slightly different lengths can be made up in order to test the faces at various positions of the micrometer spindle. It is more convenient, however, to make an independent test upon the squareness of the face of the spindle by some form of optical test involving reflection from the face as the spindle is revolved, such as follows:

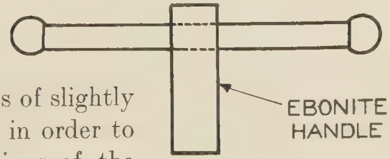


Fig. 62.

---

* For particulars of this test, see Vol. I. p. 197.

With the frame of the micrometer lightly clamped in a vice, an autocollimating telescope is set up, as in Fig. 63, so that an image of its cross-wires is formed by reflection in the face, upon which the light is directed by means of a prism. If the face is in error, the image of the cross-wires will be seen to move as the spindle is revolved, and the magnitude of the error can be readily determined by measuring the maximum movement which occurs. Failing an autocollimating telescope, errors can be detected to a sufficient degree of accuracy by allowing the reflected image of a fine wire to fall upon a screen placed a few feet away, as in Fig. 64. Assuming that the face

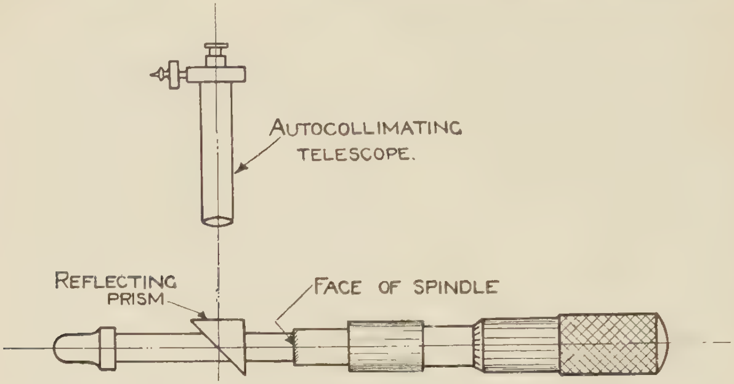


Fig. 63.

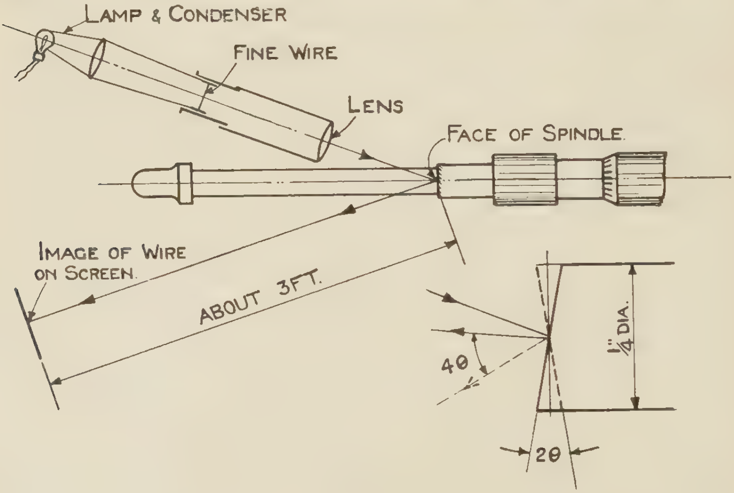


Fig. 64.

of the spindle is out of square by an angle θ, the maximum deflection of the reflected beam will be 4θ. With the screen at a distance of, say, three feet, the movement of the image will be 144θ inches. Thus, a small error in squareness of 0·0001 inch over the $\frac{1}{4}$-inch diameter of the face ($\theta = 0\cdot0004$ radians) would give rise to an easily perceptible movement on the screen of approximately 0·06 inch.

Accuracy of Reading.

Apart from errors arising from imperfections in the measuring faces, the accuracy of the readings of a micrometer depends mainly upon three factors :

(*a*) Accuracy of pitch of the micrometer screw,
(*b*) Correct adjustment of the anvil,
(*c*) Accuracy of spacing of the graduations.

The obvious method of testing the accuracy of a micrometer is to measure with it a number of gauges of known size. This method can be applied very conveniently for sizes up to an inch by making use of standard block gauges. To test the progressive error, the measurements should be made throughout the range at intervals of $\frac{1}{20}$th or $\frac{1}{10}$th of an inch. Periodic errors recurring at intervals of a revolution would not be detected by such a test ; they have to be sought by measurements made at more frequent intervals, using another series of gauges, such as 0·100, 0·105, 0·110, 0·115, 0·120 and 0·125 inch, the readings upon which all fall within the compass of a single revolution of the thimble. It is desirable to repeat this test over two or three revolutions at different parts of the screw.* This can be arranged by wringing each of the above gauges in turn on to, say, the 0·5- and the 0·8-inch block. If the micrometer is provided with a ratchet stop or friction head which is ordinarily used in taking measurements, it should also be used when calibrating the instrument.

A great advantage of the above method of test is that the micrometer is used in the same manner as when making ordinary measurements, and the results are therefore directly applicable to its practical uses. On the other hand, the accuracy to which the tests can be carried out is limited by the accuracy to which it is possible to estimate the last digit in the reading. This involves, at every point in the calibration, an uncertainty of the order of ±0·0001 inch, or ±0·00005 inch, if the instrument is graduated with a vernier. In addition, unless special gauges are provided, the method is hardly applicable to larger sizes of micrometers, such as, for example, one reading from 11 to 12 inches. The following method enables a more accurate calibration to be made of the actual travel of the micrometer screw, but leaves the verification of the zero adjustment to be made by taking a measurement on a single gauge of known length.

---

* The presence of periodic errors in micrometers is due not so much to imperfections in the micrometer screw and nut as to eccentricity in the rotating thimble carrying the graduations. The error rarely exceeds ± 0·0001 inch.

The micrometer is held rigidly and in such a position that movements of its spindle are transmitted to a sensitive indicator by means of a bell-crank lever, as in Fig. 65. The indicator should be capable of showing movements of 0·0001 inch, but need have a range of only a few divisions. The Hirth "Minimeter"* is very convenient for the purpose. With the aid of a lens to view its graduations, the reading of the micrometer is carefully set to zero. The position of the indicator is then adjusted so as to bring the pointer to about the centre of the scale, with a 0·1-inch block gauge between the face of the micrometer spindle and the contact on the bell-crank lever. Having noted the reading of the indicator, the setting of the micrometer is changed to exactly 0·1 inch with a 0·2-inch slip gauge in position. The indicator reading is again noted. This process is repeated at intervals throughout the range of the micrometer, and, by comparing the successive indicator readings with the initial one, the errors in the readings of the micrometer can be readily ascertained to about 0·00002 inch. If the block gauges used have errors exceeding ±0·00001 inch, these should, of course, be allowed for in the results.

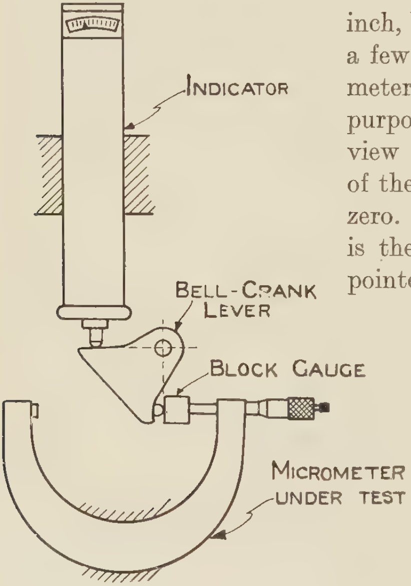


Fig. 65.

The following table gives the readings and the results obtained when testing a 4–5-inch micrometer at intervals of 0·1 inch by this method :

---

* For description, see Vol. I. p. 328.

Micrometer Setting. (Inches.)	Block Gauges. (Inches.)	Unit = 0·0001 inch.						
		Minimeter.			Difference from Zero	Difference Halved.*	Errors of Block Gauges.	Difference Corrected for Errors of Gauges. Progressive Error of Reading.
		Reading.	Repeat.	Mean.				
0·0000	0·1	2·8	2·9	2·8	0·0	0·0	0·0	0·0
0·1000	0·2	3·9	3·8	3·8	+ 1·0	+ 0·5	− 0·2	+ 0·7
0·2000	0·3	4·5	4·1	4·3	+ 1·5	+ 0·7	− 0·1	+ 0·8
0·3000	0·4	3·6	3·7	3·6	+ 0·8	+ 0·4	0·0	+ 0·4
0·4000	0·5	3·4	3·6	3·5	+ 0·7	+ 0·3	− 0·1	+ 0·4
0·5000	0·6	4·9	4·9	4·9	+ 2·1	+ 1·0	− 0·1	+ 1·1
0·6000	0·7	5·4	5·6	5·5	+ 2·7	+ 1·3	+ 0·2	+ 1·1
0·7000	0·8	5·3	5·4	5·3	+ 2·5	+ 1·2	+ 0·2	+ 1·0
0·8000	0·9	5·0	5·2	5·1	+ 2·3	+ 1·1	+ 0·1	+ 1·0
0·9000	1·0	5·2	5·4	5·3	+ 2·5	+ 1·2	0·0	+ 1·2
1·0000	0·35 + 0·75	4·9	5·1	5·0	+ 2·2	+ 1·1	− 0·1	+ 1·2

* The bell crank lever used in this test had a ratio of 2 to 1.

It is interesting to note the closeness to which the indicator readings repeat after resetting the micrometer reading at a given position. This repetition, which, in the worst case, amounts to only 0·4 division, shows that, with the assistance of a lens, it is possible to set a line on the thimble in coincidence with the datum line along the barrel to within $\frac{1}{50}$th of a division on the thimble.

The above method is applicable to any size of micrometer with a range above an inch. It is suitable also for the calibration of micrometer heads. If desired, the bell-crank lever can then be dispensed with, and the micrometer spindle be placed directly in line with the indicator. Metric micrometer screws can be tested with equal facility and accuracy by this method if millimetre block gauges are used.

The Care of Micrometers

As with all measuring instruments, micrometers soon tend to lose their accuracy unless reasonable care be exercised both in their use and upkeep. Burrs on the measuring faces, or distortion of the frame and consequent loss of parallelism of the faces, is the natural outcome of rough handling. On the other hand, even with the best of care, the accuracy of the screw is likely to deteriorate with prolonged use. Provided the wear takes place fairly uniformly along the screw, the accuracy of the instrument can be restored by taking up the backlash and readjusting the zero. After a time, however, the screw tends to wear unevenly and develops progressive errors. When this is found to exceed a certain amount (depending upon the uses to which the particular micrometer is put), the instrument should be discarded, or possibly relegated to less accurate purposes after receiving some distinguishing mark to denote its inferiority.

Particular attention should be directed to the necessity for frequently checking micrometers used in grinding-rooms. The demand for high accuracy in this production department is unfortunately accompanied by abnormal deterioration of measuring instruments on account of the presence of abrasive dust.

Burrs or local damage to the measuring faces of a micrometer can be rectified by careful treatment with a small slip of oil-stone. On the other hand, general flatness or parallelism of the faces can only be restored by relapping. To do this, the micrometer spindle should be withdrawn from the frame and mounted in a well-fitting block which has been bored and faced at one setting in a lathe. The block is rubbed over a lapping plate, as in Fig. 66, whilst the spindle is pressed gently down on to the plate and given a slow rotary motion in the block. A visual inspection of the face will indicate when the operation of lapping is complete. A final test of the flatness should be made by placing the face in contact with a proof plane or a small piece of plate-glass, when the appearance of the coloured fringes will give an accurate indication of the truth of the face. If the bands are straight, the flatness is good, and, at the same time, it may be taken that the face is square to the axis of the spindle.

If, as the result of wear, a slight lack of squareness should develop between the bore and face of the jig, this error is not directly transferred to the face of the spindle. The action of rotating the latter in the jig during the lapping process causes any such error to be distributed round the face, making it slightly conical in form, a defect which is of less consequence than a pure lack of squareness. If, on inspection, the face is found to be convex by more than 0·00005 inch, it points to an abnormal error in the jig, which should be refaced after mounting on a carefully trued arbor.

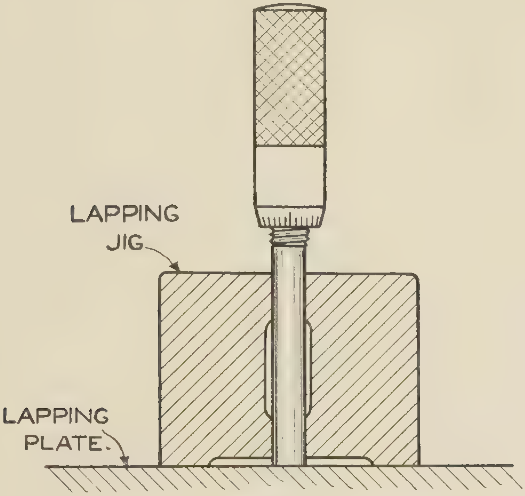


Fig. 66.

Having rectified the face of the spindle, the measuring face of the anvil can be rendered flat and parallel to it by lapping with a small, parallel-faced disc of cast-iron held between the two faces.* The face used against the anvil should be lightly charged with abrasive by rubbing on a lapping block. As this process of correcting the anvil tends to spoil the accuracy of the face of the spindle, it may be found necessary, as a final operation, to relap it in the jig. After correcting the faces, the zero of the micrometer should, of course, be readjusted.

---

* Such a disc can be readily produced by spot-grinding the faces (see Vol. I. p. 84).

A frequent cause of error with micrometers arises from accidental disturbance of the zero adjustment. A constant check should therefore be kept upon this by bringing the faces into contact, if possible, or in the case of larger sizes, by taking a measurement upon a setting gauge of known length. For this purpose it is desirable that machinists should have easy access to the necessary gauges for checking their micrometers. In this connection it may be of interest to mention that during a recent visit to a large works in the Midlands, the author was impressed by the sight of several racks of rod gauges placed at convenient positions in the machine shop, each accompanied with a bold notice, "CHECK YOUR MICROMETER". The gauges were subject to frequent inspection by a member of the gauge-room staff, who was responsible for their accuracy and general condition. It was stated by the management that since the introduction of these sets of gauges into the shops there had been a noticeable reduction in the amount of work rejected on final inspection.

Micrometers for Special Purposes

Depth Micrometer.

In addition to the ordinary form of micrometer described above, which is used for measurements across external surfaces, and the internal form used for measuring between surfaces,* there is yet another type for measuring the distance between two surfaces facing in the same direction, such as those of a step or the upper and lower surfaces of a recess. These depth micrometers, as they are commonly called, usually take the form shown in Fig. 67. The micrometer head has a

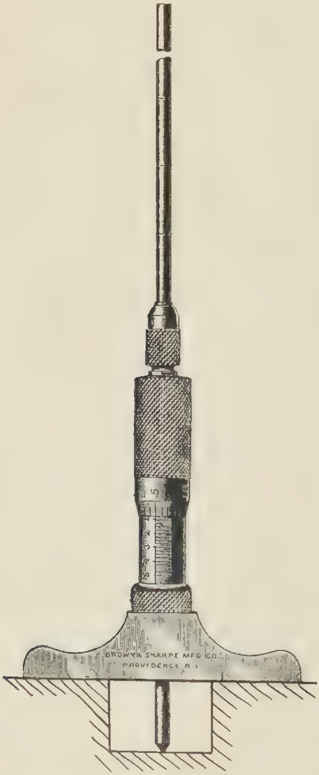


FIG. 67.

---

* See Chapter VIII. on "Internal Measurements."

central spindle which projects through a hole in a flat, rectangular base. The projection of the spindle is recorded on the graduated barrel and thimble in the usual manner. The travel of the micrometer is generally limited to half an inch, but the range of measurement is increased by the measuring spindle having a series of small grooves, accurately spaced at half-inch intervals, into any one of which the spring fingers on the end of the thimble can be gripped.

Spherometer.

A modified form of the depth micrometer is used for measuring the curvature of spherical surfaces. The instrument consists of a tripod (Fig. 68), the legs of which are turned down at the ends to conical points which lie at the corners of an equilateral triangle. This tripod carries at its centre a vertical, sharp-pointed micrometer screw, fitted at the upper end with a graduated disc. The screw usually has a pitch of $\frac{1}{2}$ mm., and the disc 500 divisions. The divisions on the dial are read against the bevelled edge of a vertical plate, a scale upon which serves to record complete revolutions of the disc.

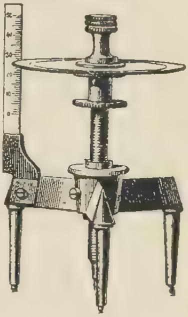


FIG. 68.

To determine the curvature of a surface, the tripod is stood upon it and the point of the micrometer screw brought down so as to make contact, the indication being given by a tendency for the tripod to rock or rotate about the point of the screw. If the difference between this reading of the micrometer and that obtained on a truly flat surface, such as a proof plane, be h, the radius of curvature of the surface is given by

$$R=\frac{1}{2h}(h^2+\frac{1}{3}a^2),$$

where a is the side of the equilateral triangle formed by the feet.

In order to overcome the difficulty of accurately measuring the distance a between the conical feet, and at the same time eliminating the error arising from slight unavoidable rounding of the points, later designs of this instrument, such as the Aldis type, Fig. 69, use steel balls at the supports. The spacing of the balls is then readily obtained from micrometer measurements made over the outsides of them. Due allowance has, of course, to be made for the size of the balls in the final result. In this improved design of spherometer the micrometer is held in an inverted position, and, in order to deal with surfaces of different sizes, several supporting rings are provided with each instrument, as shown. The surface to be measured is placed upon the three supporting balls of the appropriate ring, and the ball-ended point of the micrometer screw advanced up towards it until contact is indicated by the readiness with which it is possible to rotate the body about the central point. The zero reading is obtained, as usual, on an optical flat.

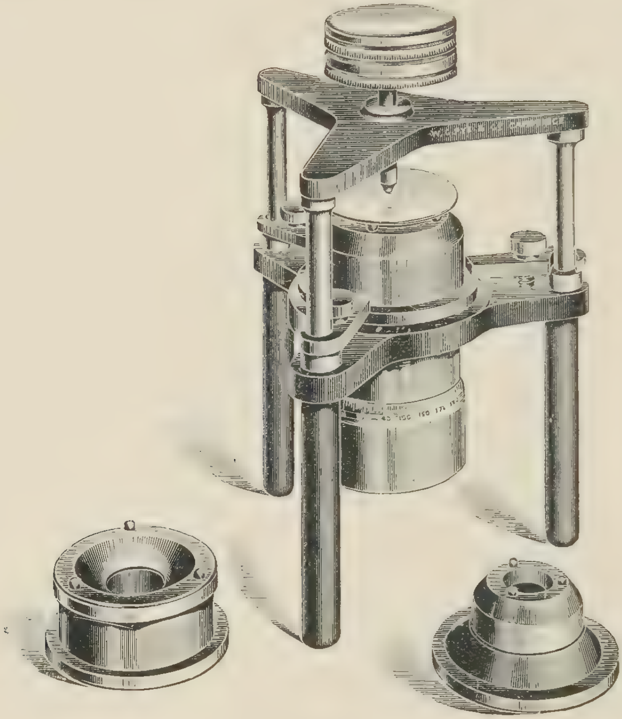


FIG. 69.

The Cambridge " Crack " Micrometer.

An interesting application of the screw micrometer is in the instrument designed by the Cambridge Instrument Company for measuring relative movements between the masonry on either side of a crack in a structure. Such measurements are important in cases of subsidence of buildings, since a series taken over a period of time gives an indication of the rate of development of the trouble.

The measurements are carried out in three directions upon two steel pegs, $\frac{1}{2}$-inch diameter, cemented into holes in the masonry, one on each side of the crack to be investigated. A jig is used to ensure that the pegs are fixed parallel to each other, and at a distance apart to suit the measuring instrument. A direct measurement of variation in the width of the crack is obtained by the arrangement shown in Fig. 70. The balanced frame holding the micrometer hangs in vees upon one of the pegs, and the micrometer is adjusted until its tip just makes contact with the inside of the other peg, when the whole instrument is rocked slightly about its support.

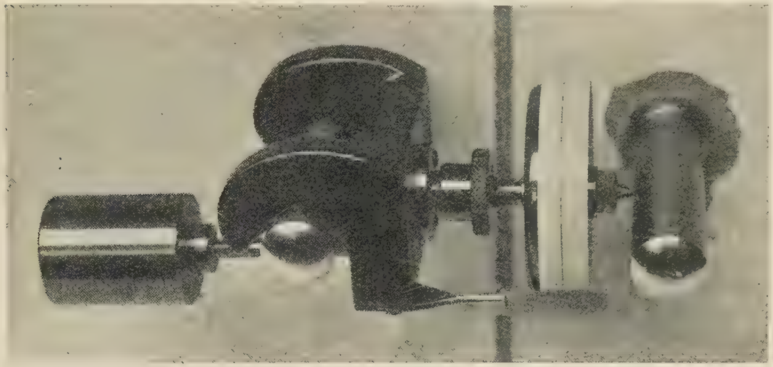


Fig. 70.

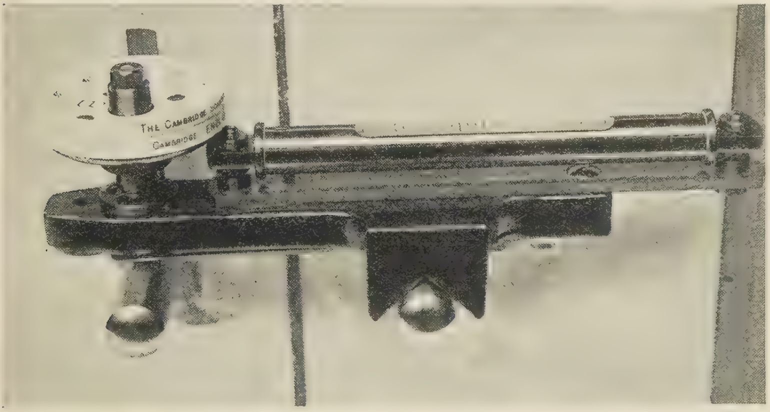


Fig. 71.

A vertical shearing, or tangential, movement between the two sides of the crack is detected by the levelling arrangement of Fig. 71. This instrument rests across both pegs, one being located in a vee.

The micrometer screw above the other peg is rotated so as to bring the bubble of the level to its central position. Any alteration in the micrometer reading obtained on another occasion gives a measure of the relative vertical movement which has taken place between the pegs in the interval.

Finally, horizontal movements parallel to the pegs are measured by a third micrometer, shown in Fig. 72. This also rests in a vee upon one pin, and is slid towards the wall until the end of one of the arms makes contact with the rounded end of the second pin. The micrometer is then screwed up until its point makes contact with the end of the supporting pin. If desired, measurements can also be made as a check by transferring the micrometer to the other peg and using the opposite arm.

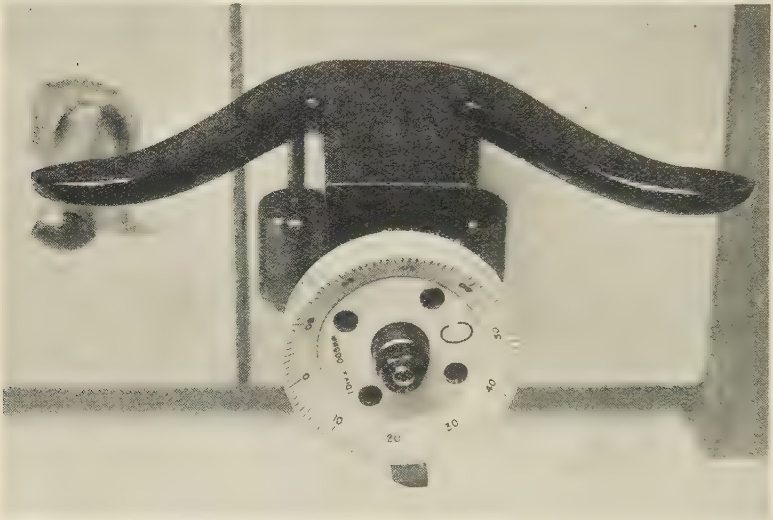


Fig. 72.

In each instrument the micrometer screw has a pitch of $\frac{1}{2}$ mm., so that each of the 100 dial divisions corresponds to a movement of 0·005 mm.

In a defective building it is generally desirable to have several sets of pegs, so as to be able to record the movements in different positions. Only one set of micrometers would be needed, however, as they can be carried from point to point and quickly placed in position upon the pegs ready for the measurements. If the measurements are to extend over a long period, it is a wise precaution to check the micrometers periodically upon a pair of pegs let into a solid block. Any wear of the contacts or accidental zero shift is then detected and can be allowed for in subsequent measurements.

ADDITIONAL REFERENCES FOR CHAPTER II

"Making the Almond Micrometer," *Amer. Mach.*, vol. 53, p. 605 (1920). (Complete description of methods of manufacture, screw cutting, graduating, etc.)

"Manufacturing a Precision Tool (Micrometer)," *Amer. Mach.*, vol. 59, p. 903 (1923).

"Lapping Micrometers," V. E. Snow, *Amer. Mach.*, vol. 48, p. 380 (1918). (Method of truing faces.)

"Lapping Micrometers," H. L. Van Keuren, *Amer. Mach.*, vol. 64, p. 871 (1926).

"Wear of Micrometer Screws," *Machinery*, vol. 27, p. 521 (1926).

"Lindquist Ten Thou' Micrometer," *Amer. Mach.*, vol. 51, p. 1066 (1919). (Differential micrometer screw having 40 and 50 T.P.I.)

"Blush Multiple Micrometer," *Amer. Mach.*, vol. 53, p. 235 (1920).

"Direct Reading Micrometer," *Engineering*, vol. 121, p. 60 (1926).

"Accuracy Requirements for Micrometers and Magnifying Levers," G. Berndt, *Der Betrieb*, No. 9, p. 280 (February 1922).

"Testing the Accuracy of Micrometers in Common Use," C. A. Hubbell, *Amer. Mach.*, vol. 53, p. 209 (1920). (Summary of results of test carried out on large number of micrometers in commercial use.)

"Periodic Errors of Micrometer Screws," R. Mecke, *Zeit. für Instrument.*, vol. 42, p. 147 (1922).

"Schraubenmikrometer," p. 129, *Grundlagen und Geräte technischer Längenmessungen*, G. Berndt and H. Schulz (Berlin, 1921).

"Machines for Testing Micrometer Screws," p. 389, *Die Gewinde*, G. Berndt (Berlin, 1925).

"Springing of Micrometer Frames," G. Berndt, *Der Betrieb*, vol. 3, p. 574 (1921).

"The Micrometer Head in Toolwork," *Amer. Mach.*, vol. 48, p. 59 (1918).

"Inspection of Micrometer Spindles at the Zeiss Works," *Amer. Mach.*, vol. 70, p. 175 (1929).

CHAPTER III

MEASUREMENTS WITH SCALES

In the earlier part of Volume I. the subject of line standards was considered in connection with the fundamental standards of length, the yard and the metre.* Descriptions were given of these standards, together with others used in laboratories as secondary standards. Reference was also made to the types of scientific apparatus employed for comparing lengths on two or more independent scales, and for determining the accuracy of spacing of the subdivisional lines on a single scale. It is now proposed to devote some space to the application of scales to measurements associated with engineering workshop practice.

Accuracy of Scale Measurements.

The accuracy obtainable by the use of a scale, or rule, depends upon the type of scale, the clearness of its graduations, the accuracy of their spacing and the methods employed for carrying out the comparison between the distance to be measured and that defined by the graduations on the scale. As regards the latter, the accuracy to which it is possible to measure, for example, the length of a metal bar, using an engineer's steel pocket-rule divided into 64ths or 100ths of an inch, is of the order of 0·01 or 0·02 inch. With the assistance of an eye-glass, fractions of the small scale divisions can be estimated and the accuracy of comparison raised, under favourable conditions, to about ±0·002 inch. The provision of a vernier enables the uncertainty to be reduced still further to about 0·001 inch. Finally, it is possible to compare the lengths of end gauges with the distances between graduations on a well-graduated scale to an accuracy of ±0·00001 inch, when the latter is used in conjunction with a suitably designed machine.† To obtain absolute values for such measurements, it is necessary, of course, to take account of any inaccuracies in the graduations of the scale used. So far as the ordinary steel rule is concerned, those of the well-known makes may be relied upon to a figure which is well beyond the accuracy to which they are ordinarily used. In the case of measuring machine scales, since the errors in dividing may amount to 0·0001 inch, it is necessary that they should be calibrated and the errors at the various graduations tabulated before the fullest value can be obtained from the machine.

---

* See Vol. I. Chapter II.

† For description of such machines, see Vol. I. Chapter XVII.

Steel Scales.

The ordinary type of engineer's rule consists of a parallel strip of tempered steel varying in section from about $\frac{3}{4} \times \frac{3}{100}$ inch for the shorter lengths, to about $2 \times \frac{1}{10}$ inch for those up to 6 feet or so. One or both faces are graduated towards the edges either in inch or metric units. In the latter case, the graduations are usually either in millimetres or half-millimetres, but in the case of English measure there is great variety in the systems of subdivision, both in fractional and decimal parts of an inch. The finest graduation met with is $\frac{1}{64}$ or $\frac{1}{100}$ inch.

In addition to the ordinary types of rules, there are certain special forms particularly suitable for carrying in the pocket, such as the narrow, flexible type and the folding variety shown in Fig. 73. Stainless steel rules are now also obtainable. These retain their bright finish indefinitely and are consequently easier to read than a rule of ordinary steel, which, after a time, usually becomes dull and blackened.

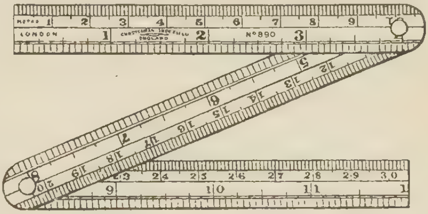


Fig. 73.

The graduation lines on steel rules are generally etched, and are about 0·003 inch in width, which is about the minimum for comfortable use with the naked eye. The etching process gives the lines a dead-black appearance, which makes them appear in strong contrast against the polished surface of the rule.

Steel Tapes.

The maximum length up to which steel rules are ordinarily made is about 6 feet. Measurements beyond this are usually carried out with flexible steel tapes. These are obtainable up to 100 feet in length, conveniently coiled inside a case, as in Fig. 74. The section of the steel ribbon varies from $\frac{1}{4}$ to $\frac{3}{8}$ inch in width by about 0·02 inch in thickness. It is customary for the graduations and numbering on such tapes to be in relief, as in Fig. 75. This is done by a special process in which the whole surface of the tape, with the exception of the lines and figures, is etched to a dull matt or even black finish. The bright figures and graduation then show up very clearly against this dark background. Since the length of a tape is dependent upon the tension under which it is used, the makers usually specify the correct pull to be applied. This is usually of the order of 10 lb.

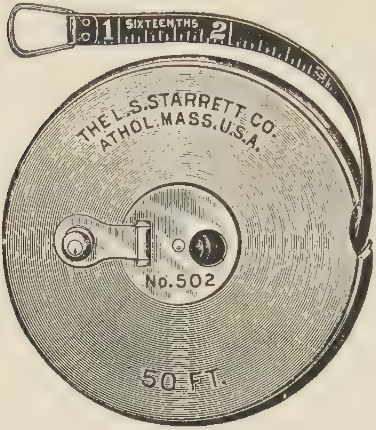


Fig. 74.

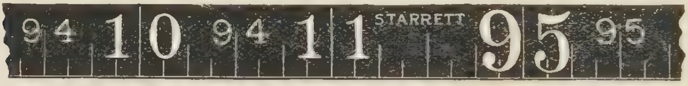


Fig. 75.

Use of Tapes for Measuring Cylinders.

In addition to ordinary measurements, tapes are frequently used for determining, by circumferential measurements, the diameters of large parts such as turbine rotors and casings, for which the usual forms of callipers or gauges become rather unwieldy. Tapes can be purchased specially for this purpose, the graduations being such that the reading obtained on wrapping the tape round or inside the part gives the equivalent diameter directly. It need hardly be mentioned that the method fails to give any indication as to the uniformity of the diameter under test, and this, of course, is of importance when the question of assembly of components is concerned. It is quite possible, however, with fairly rough measuring tools to ascertain what variations are present even in large diameters without any reference to absolute size, and, if these tests show satisfactory uniformity, the absolute value of the mean diameter can then be determined with a tape.

When using an ordinary tape for the purpose indicated above, it is to be remembered that, in wrapping it round a cylinder, a tape follows a helical curve, as in Fig. 76. Neglecting, for the time being, the effect of its thickness, the tape gives a measurement l along its length, which is the distance between two graduations such as a and b. The circumference required, however, is the diagonal distance ab, which is equal to $\sqrt{(l^2+w^2)}$, where w is the width of the tape. Since w is usually small as compared with the circumference being measured, the latter may be written as $l(1+\frac{1}{2}\frac{w^2}{l^2})$. Hence, the correction to be applied to the measurement l is $+w^2/2l$.

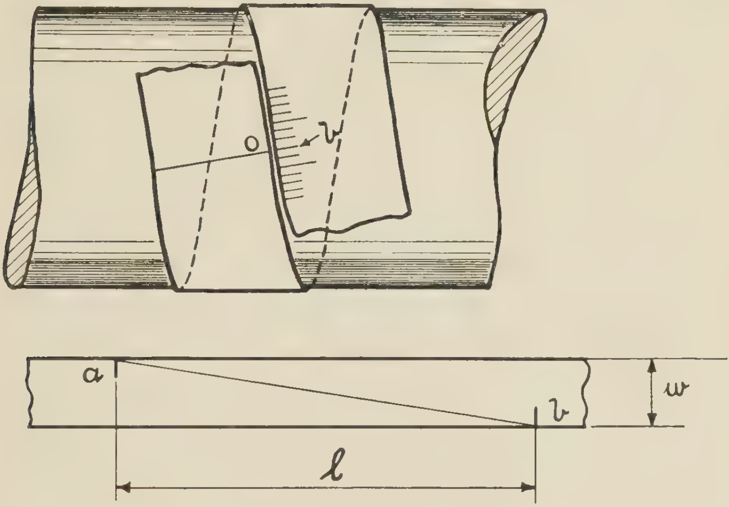


Fig. 76.

Generally, this correction is small enough to be neglected. For example, in measuring the circumference of a 36-inch cylinder with a tape half an inch wide, the correction amounts to only +0·0011 inch, *i.e.* less than 0·0005 inch on the diameter required. Unless the tape is finely subdivided, it would not be possible to read the length l by estimation between the graduations to better than perhaps 0·01 inch, so that it would be useless to take account of a correction of such relatively small magnitude.

To increase the accuracy of the measurement, the tape should be ruled with fine lines at intervals of, say, 0·1 inch, with the last few intervals at the zero end further subdivided to 0·01 inch. It should then be possible to estimate the length to the third place of decimals. Under such circumstances, the correction referred to above might become significant when dealing with smaller sizes of cylinders, especially if a rather broad tape be used.

The whole of the helical effect can be eliminated by "halving" the ends of the tape as in Fig. 77. It can then be wrapped round the cylinder circumferentially, and the two ends brought side by side for purposes of reading the measurement.

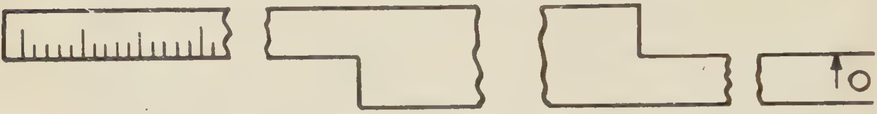


FIG. 77.

A more important correction is that which should be applied on account of the thickness of the tape. In wrapping a tape round a cylinder as in Fig. 78, its neutral section remains unstrained, but the fibres along the outer, graduated surface become stretched by an amount $\pi \times t$, where t is the thickness of the tape. The reading, R, of the tape therefore corresponds to the circumferential length at the position occupied by the neutral section of the tape. The circumference of the cylinder is less than this length by $\pi \times t$, and is therefore equal to $(R - \pi . t)$, *i.e.* to the measurement as given by the tape reduced by π times the thickness. It is hardly necessary to point out that, when measuring an inner circumference, the reading given by the tape should be increased by $\pi . t$. Since the thickness of the tape, t, is usually of the order of 0·02 inch, the magnitude of the

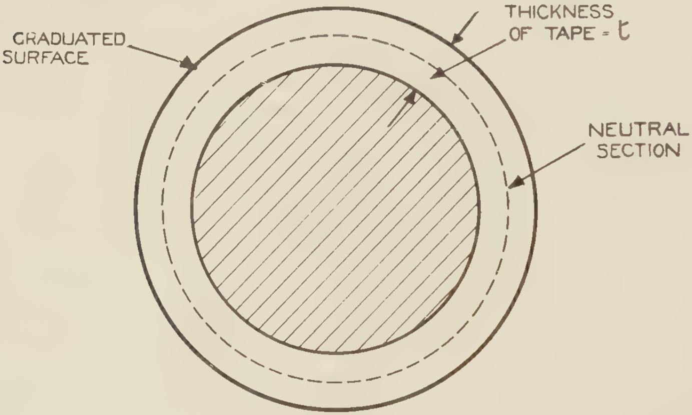


FIG. 78.

correction on the circumferential measurement amounts to about $\frac{1}{16}$ inch, and clearly demands attention.

An interesting example of the use of tapes occurs in connection with the measurements of motor rims as standardized by the Society of Motor Manufacturers and Traders. Here, the tape takes the form of a limit gauge for the circumference. One end of it is finished square, and, when wrapped round the rim as in Fig. 79, it falls beneath a metal plate riveted to the other end. This plate has an elongated hole through which the plain end can be seen and its position noted with respect to two limit lines scribed across the face and the bevelled edges of the hole, as shown. With the assistance of small handles attached to its ends, the tape is pulled taut round the rim; if the plain end then occupies a position between the two lines, the rim is passed as satisfactory. Tapes of different lengths are required for each standardized size of rim. The limit on the circumference is ±3 mm., so that the limit lines are spaced 6 mm. apart. In graduating these tapes, allowance is made for their thickness, and, since they are wrapped directly round the circumference, the question of a correction on account of helical form does not arise.

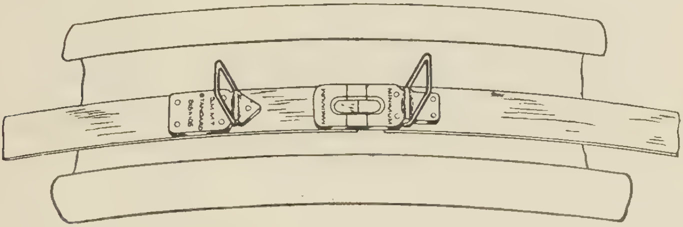


FIG. 79.

Scales on Glass and other Materials.

In dealing with the subject of scales, reference should not be omitted to the type introduced some years ago by Messrs. Rheinberg and Company. These scales are graduated on glass about $\frac{1}{8}$ inch thick by a special filmless photographic process. The graduation lines and the numbering are formed in untarnishable metal in the surface layer of the glass, and are irremovable by wiping or even scraping. Such scales can be obtained with subdivisions as fine as 0·005 inch. Although hardly applicable to workshop practice, these scales are useful in inspection rooms and drawing offices. They are intended to be used with the graduated surface in contact with the object or drawing to be measured, thus eliminating any inaccuracies due to parallax.

So far as accuracy is concerned, it may be mentioned that a 3-inch scale of this type, tested by the author, was found to be correct to well within 0·001 inch both on the overall length and at a few subdivisions selected at random.

For drawing office work, scales are generally made of boxwood, a material which, if carefully seasoned and finally coated with shellac varnish, is reasonably free from changes due either to age or fluctuations of atmospheric conditions. Ivory is sometimes used for the same purpose, but should be avoided owing to its strong tendency to shrink with time ; its length is also affected to a very marked degree by changes in the humidity of the atmosphere.

There are many systems of graduating draughtsmen's scales according to whether they are to be used by engineers, architects or surveyors. For engineering work the graduations are often made to suit drawings to scales of $\frac{1}{1}$, $\frac{1}{2}$, $\frac{1}{4}$, and $\frac{1}{8}$ size. For large size mechanical and architectural drawings the " Armstrong " scale is very convenient. This has eight scales, viz. $\frac{1}{8}$, $\frac{1}{4}$, $\frac{3}{8}$, $\frac{1}{2}$, $\frac{3}{4}$, 1, $1\frac{1}{2}$ and 3 inches to the foot. The scales are openly divided, and each is subdivided into inches over a division of 1 foot outside the zero graduation.

" Line-to-Line " Settings.

The operation of " zero indicators ", such as are used on certain types of measuring machines, involves the setting of a movable pointer, or mark, to a fiducial line. In making such setting, the effect of experimental errors upon the reading of the instrument depends largely upon the magnification factor of the indicator, but the accuracy of the reading is also influenced to a considerable extent by the general definition of the two marks which have to be brought together.

With certain optical indicators the setting is made by superposing an image of a line, or of a fine wire, upon a fiducial line, the latter either being situated in the eyepiece of the microscope or, in the case of a projected image, ruled on a chart. In either case, the setting presents difficulties, especially if the image extends the whole length of the fiducial line. Even under the best condition, when the image and the line are of equal thickness, it is still a matter of deciding the position of coincidence which corresponds to a minimum combined thickness of image and line.

The accuracy to which settings can be repeated is considerably improved if the fiducial line is converted into a pair of parallel lines between which the image has to be placed symmetrically, as in Fig. 80. Equality in thickness between the lines and the image is no longer of importance, since, in making a setting, the object is to equalize the widths of the white spaces on each side of the line. It is clear that an error in making this estimation is halved so far as the position of the line is concerned.

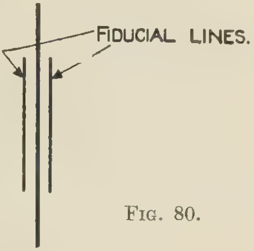


Fig. 80.

In the case of indicator pointers or slides, the difficulty of superposing one line exactly over another does not arise; the setting involves the placing of one line continuous with another. Given good lines with well-defined edges, the accuracy to which such settings can be made is surprisingly high, even with the naked eye: with the assistance of an eyeglass, an accuracy of 0·001 inch is readily obtained. The noticeable discontinuity of two lines displaced by only this amount can be seen on the scale and vernier of a sliding calliper reading to 0·001 inch; having identified the "coincidence line" on the vernier, one has only to look at one or other of the adjacent lines to see the effect mentioned.

It has been pointed out by E. M. Eden that the accuracy of "line-to-line" setting is improved if each of the single lines is replaced by a pair at slightly different distances apart. This can be seen if we consider, for example, a case where it is possible to set a single line opposite another fixed line with a maximum uncertainty of, say, ±0·001 inch; in other words a displacement of 0·001 inch from the true setting is beginning to be perceptible. Now, suppose each line is duplicated as in Fig. 81, the distance between one pair of lines being made 0·001 inch different from the other pair. The extreme range of possible settings is shown by the outside diagrams,

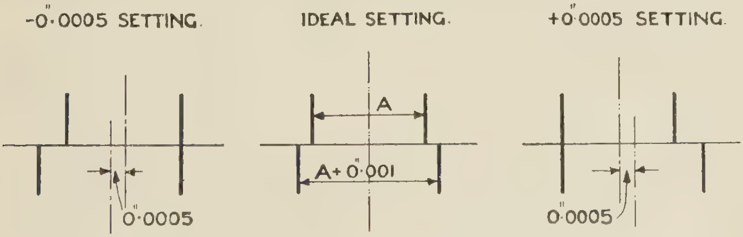


Fig. 81.

in which the outer lines of each pair are just visibly displaced in opposite senses (the effect is, of course, exaggerated in the figure). In these extreme positions, however, the centres of the two pairs of lines are displaced by only 0·0005 inch, so that the uncertainty of setting is reduced to within ±0·0005 inch, which is half the possible error if single lines are used.

The same effect is obtained if the spaces between the two pairs of lines are blackened in. We then return to two single marks, one of which is just perceptibly wider than the other, as shown enlarged in Fig. 82. In making a setting, both edges of the pointer have to be made to coincide as closely as possible with the edges of the mark.

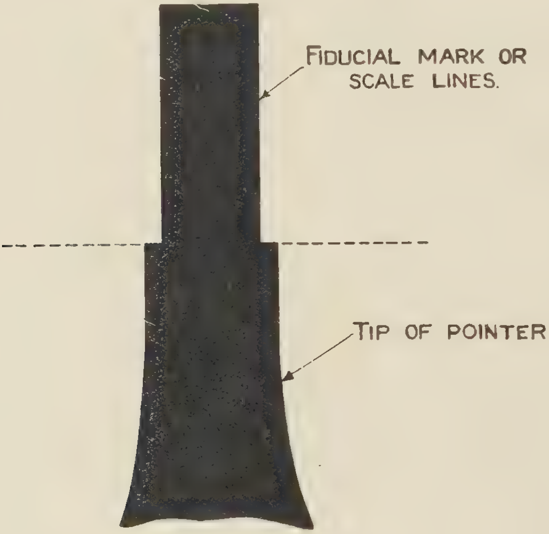


FIG. 82.

When calibrating an instrument having a scale and a movable pointer by comparing its readings with those of a standard instrument, arrangements should be made that the readings or settings of the test instrument occur exactly at scale divisions, so that advantage is taken of the precision of line-to-line settings. The errors of the readings can then be obtained from corresponding readings of the standard instrument, the scale of which is usually more openly divided, and therefore capable of being read more accurately to fractions of its divisions.

A typical application of this principle occurs in the method described on page 48 for the calibration of a micrometer screw.

Although the micrometer itself may be graduated to read to only 0·001 inch, it is possible to determine the errors of its readings to the order of a fiftieth of this amount, *i.e.* 0·00002 inch.

Magnifying Glasses.

When taking measurements with finely graduated scales, it is necessary to use some form of magnifying glass in order to obtain a clear view of the graduations and to subdivide them further by estimation. Such glasses may take the form of hand-lenses such as are shown in Fig. 83. The type on the left consists of a number of simple lenses of different focal lengths which may be used individually or in combination, the lenses being mounted in a suitable holder, which serves also to protect them when not in use. Where a flat field is desired, a corrected lens of the form shown at the right of the figure can be used. Such lenses can be obtained to give magnifications of from $2\frac{1}{2}$ to 20 times.

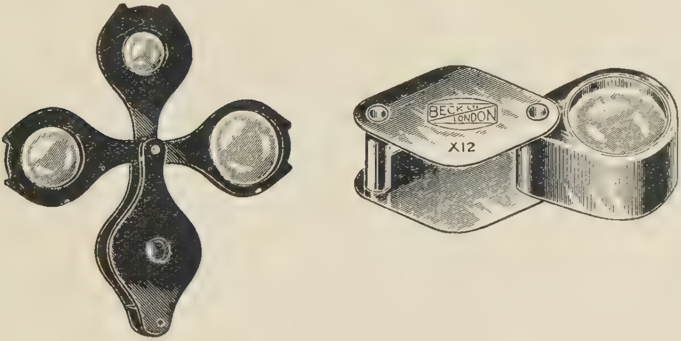


Fig. 83.

When using a magnifying glass it is often necessary to have both hands free for purposes of manipulation ; the watchmaker's type of glass can then be used, the shape of the mount being convenient for holding in the eye-socket. The lens is mounted in a light shell of wood, or aluminium (Fig. 84), or is supported in a wire frame as shown at the right of the figure. The latter form, besides being particularly light and easy to hold in the eye, can be conveniently folded into a small compass for the pocket ; in addition, it does not fog when in use.

The strain which usually arises from protracted use of an eyeglass can be avoided by adopting a binocular type as in Fig. 85. This pattern, introduced by Messrs. Watson and Sons, has a pair of lenses suitably mounted in an ordinary spectacle frame, with their axes so arranged as to give a clear, magnified view of the scale, or object, to be examined. It has the additional advantage over a single lens in

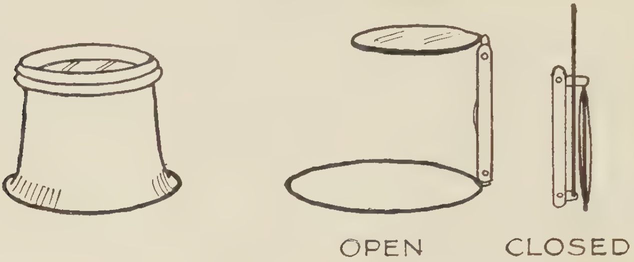


Fig. 84.

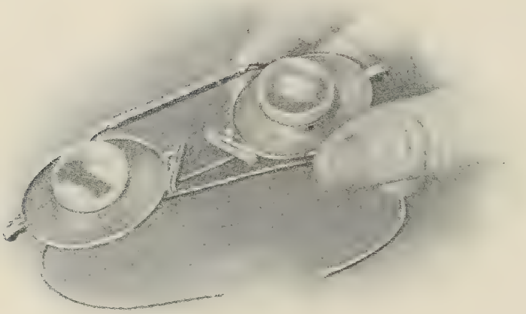


Fig. 85.

giving a stereoscopic view, which is of importance if any manipulation or adjustment of the object under view is required.

Uses of Scales on Measuring Instruments.

It has been pointed out by J. E. Sears * that, in addition to their ordinary uses for linear measurements, scales are employed in carrying out practically all forms of measurements, both industrial and scientific.

The fundamental purpose in designing measuring instruments and meters is to translate the quantity to be measured into some simple form of motion, or displacement, measurable on a scale. For example, in measuring electric current with an ammeter, the mechanism of the instrument is such that the strength of the current

---

* *Dict. of Applied Physics*, vol. iii. p. 618.

is recorded on a scale by a pointer whose movement from the zero position is caused by, and varies with, the flow of current through the instrument. The scale of the instrument is marked off to represent appropriate electrical units, and fractions of the divisions can be readily estimated if desired. The spacing of the scale divisions of such instruments is determined by their individual operating mechanisms, and is generally quite independent of any standards of length. The scale may or may not be uniformly divided; in either case, the value of its divisions in terms of the unit of the quantity to be measured is determined by comparison with readings taken on a standard instrument or by reference to first principles.

There is, however, a particular class of measuring instrument which deals with linear measurements, the results of which are observed directly on a scale. It is to this class that attention will be confined.

Vernier Calliper Gauge.

Perhaps the best known form of measuring instrument incorporating a scale is the vernier calliper gauge, Fig. 86. This is used

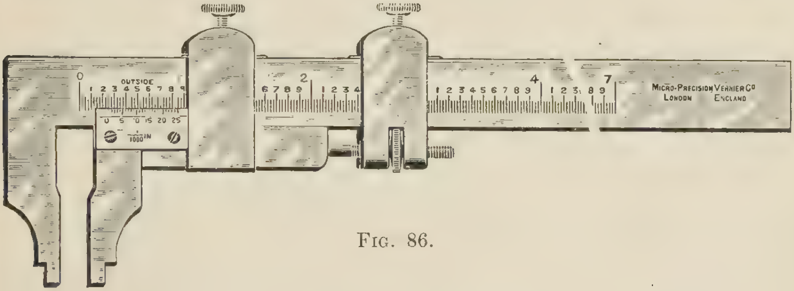


Fig. 86.

for end measurements, both external and internal, and is capable of an accuracy of the order of 0·001 inch. The measurements are made either between, or outside, the pair of hardened steel jaws shown; one of these is formed solid with the beam of the instrument, whilst the other is capable of being slid along it. The sliding jaw is coupled by a finely-threaded screw and nut to an auxiliary slide. By clamping the latter to the beam and rotating the knurled nut, a fine adjustment of the sliding jaw is obtained, which, after being set to the required reading, or to suit the size of the object being measured, can also be clamped to the beam by its own locking screw. The inside surfaces of the jaws are made flat and parallel, whilst, for purposes of internal measurements, they are ground cylindrically on the outsides at the ends.

The setting of the jaws is read on a scale engraved along the beam. When in inch units, the scale is divided into fortieths, and a 25-division vernier attached to the sliding jaw enables readings to be made to a thousandth of an inch. The reading obtained corresponds to the distance between the jaws; when making an internal measurement it has to be increased, therefore, by the combined thickness of jaws, which is usually made some convenient dimension such as 0·250, 0·300 or 0·500 inch.

Some makers of these instruments provide a second scale and vernier on the reverse side of the beam to enable inside measurements to be read off directly. This, however, appears rather unnecessary, and better advantage is obtained if a metric scale be added so that the instrument can be used for measurements in either the British or Metric systems. In the latter case, readings can be obtained to 0·02 mm.

Vernier callipers are made in a variety of sizes, with capacities ranging from about 3 to 36 inches. The jaws are sometimes specially shaped to suit particular measurements, such as those of gear teeth. These modified forms will be dealt with under the particular classes of measurement concerned.

Vernier Height and Depth Gauges.

Other examples of the application of scales to contact measurements occur in instruments used for measuring distances above or below a surface.

The vernier height gauges as made by Messrs. Brown and Sharpe for use on a surface plate consist of a base (Fig. 87) to which is attached a vertical graduated bar forming a support for the sliding jaw. The projecting part of the latter has both its upper and lower surfaces finished parallel to the base block, to permit of measurements either over or under a surface. The instrument is particularly useful for checking dimensions of jigs. When required for marking-off purposes, a scribing attachment can be clamped to the slide, as shown in the figure. The scale upon the vertical bar is usually graduated in the same manner as for a

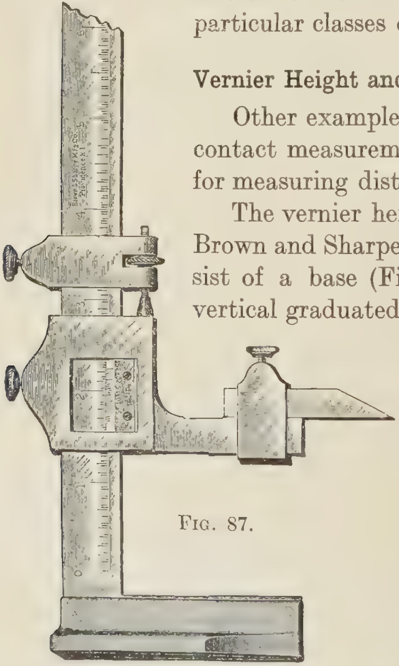

Brown & Sharpe Mfg. Co.

Fig. 87.

vernier calliper ; with the assistance of a vernier on the slide, readings can be obtained to 0·001 inch or 0·02 mm.

The Brown and Sharpe gauge for measuring the depth of holes, the distance from a plane surface to a projection, etc., takes the form of a graduated blade, Fig. 88, which can slide through a base, the projection of the end of the blade below the base being given by the reading of the scale. The particular instrument illustrated is graduated in both inches and millimetres, and each scale can be read by its own vernier. A fine adjustment screw is provided, as in the case of the vernier calliper described above.

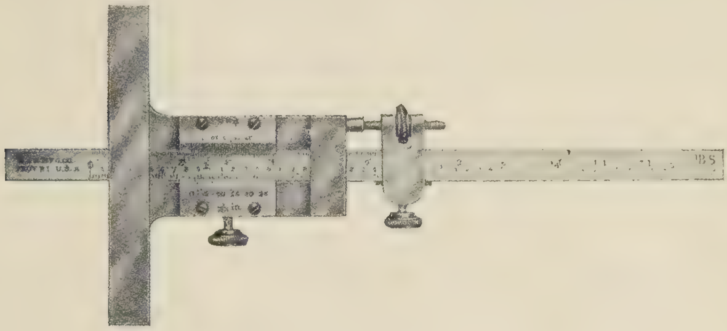


Fig. 88.

Thickness Gauge.

A simple form of gauge for measuring the thickness of ship plates, boiler plates, etc., which makes use of a scale is shown in Fig. 89.

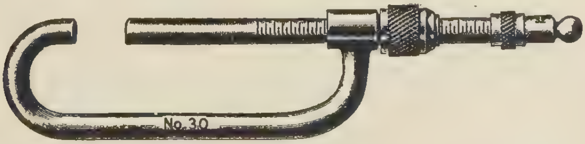


Fig. 89.

The hook-shaped frame is either passed round the edge of the plate, or is inserted through a hole drilled in it, and the sliding rod is then pushed home so as to bring the two contact faces up to the plate. The small, knurled, friction sleeve is then slid down the rod as far as it will go, after which the latter may be withdrawn from the frame, and the position occupied by the abutting face of the sleeve noted against the scale of $\frac{1}{32}$nds graduated on the rod.

Wedge Gauges.

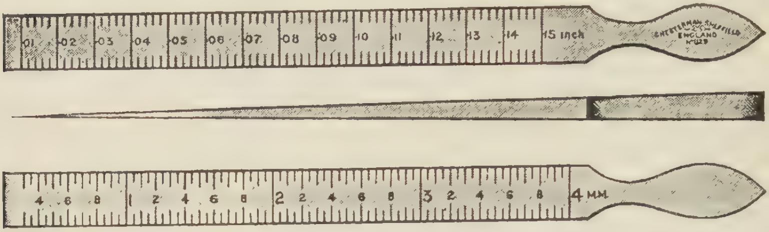


Fig. 90.

A further example of the use of scales for contact measurements is to be found in the wedge gauge, Fig. 90. The particular type of gauge made by Messrs. Chesterman and Company consists of a steel wedge about $\frac{7}{16}$ inch wide, uniformly tapered along its length, and graduated on its sides with scales giving the thickness at any position. The taper is approximately 1 in 30. The scale on one face ranges from 0·01 to 0·15 inch, and has a graduation for each 0·002 inch, whilst the opposite face is graduated in metric units from 0·3 to 4·0 mm., with divisions representing increments in thickness of 0·05 mm. The gauges are made in sets of four, of which the one illustrated is the smallest. The others cover ranges of thicknesses from 0·12 to 0·26, 0·25 to 0·39 and 0·37 to 0·51 inch respectively. These gauges can be used for such purposes as measuring the width of gaps, setting outside callipers, etc.

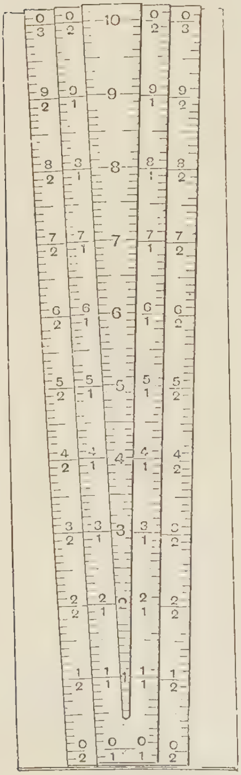


Fig. 91.

A combination gauge on the same principle, but covering a more extensive range from 0·05 to 3 inches, is shown in Fig. 91. This is by the same makers as before, and is formed of three plates with tapered sides, mounted one above the other on a base about 12 inches in length. Each plate covers a range of an inch, and bears a scale the divisions of which are spaced about $\frac{1}{8}$ inch apart, and represent increments in the widths of the plates of 0·01 inch.

Scales used on Micrometers.

Before leaving the subject of scales, some reference should be made to the scales associated with micrometer screws of all descriptions, particularly those engraved round the periphery of the dials attached to the rotating part. The linear scales are worthy of but little attention, since their function is merely to indicate the number of complete revolutions from a certain datum. If desired, they could be replaced by a simple counting mechanism without affecting the accuracy of the reading. The accuracy of the instrument depends upon the truth of the pitch of the micrometer screw, together with satisfactory dividing of the graduated dial, which serves to give accurate subdivisions of the pitch. Although the dials are divided so that each division represents a convenient linear unit of displacement such as 0·001 inch, 0·001 mm., etc., the scale really possesses no absolute value, and its whole purpose is fulfilled if the circumference of the dial is divided in a uniform manner into the requisite number of parts. With modern appliances for circular dividing, little trouble is experienced due to lack of uniformity of spacing of the divisions. Errors of a periodic nature, however, are likely to arise if the axis of rotation of the dial is not coincident with the centre about which it was graduated.

ADDITIONAL REFERENCES FOR CHAPTER III

“Line Standards of Length,” *Dict. of App. Physics*, vol. 3, p. 465 (1923).
“Comparators,” *ibid.* p. 232.
“Die technischen Strichmasse,” *Grundlagen und Geräte technischer Längenmessungen*, G. Berndt and H. Schulz (Berlin, 1921).
“Steel Tapes for Measuring Large Diameters,” G. C. Reilley, *Amer. Mach.*, vol. 62, p. 26 (1925).
“Note on Estimation of Tenths,” P. Kirkpatrick, *Phys. Rev.*, vol. 19, p. 545 (1922).

CHAPTER IV

WORKSHOP MEASURING INSTRUMENTS

Whilst there is no definite demarcation between the types of measuring tools used in workshop and in inspection rooms, there are certain instruments which are perhaps more commonly associated with the former, and it is proposed to devote some space to their description.

Most of the tools and instruments described below are the standard designs of Messrs. Brown and Sharpe, the original makers of a large proportion of the accurate, small, measuring tools and appliances used in modern tool rooms.

Tools used for Marking Off and Setting Up.

(i) *Surface Plates and Straight Edges.*—It will be seen in Chapter X that the surface plate and straight edge form the basis of accurate machining operations and, therefore, of accurate measurement. A description is given there of the method of generating a true plane surface, together with typical examples of surface plates and straight edges.

(ii) *Scribing Block.*—The most useful tool for marking off work preparatory to machining is the scribing block, or surface gauge, as it is sometimes called. It is used in conjunction with a surface plate, and consists of a heavy base, Fig. 92, to which is hinged a pillar carrying the scriber in a universal clamp. The point of the scriber is set to the desired dimension by the use of a scale or end gauges resting on the plate. This setting is facilitated by a fine adjustment of the inclination of the pillar obtained from the set-screw A, in the base, operating on the end of the short lever shown. A clamp screw enables the pillar to be fixed, once the correct setting is made.

The base has a vee-groove along its lower face which enables it to be used upon cylindrical work. The two pins B can be pressed down and made to project beyond the lower surface of the base, thus forming a guide if it is required to scribe a line parallel to the edge of the surface plate or casting upon which the base is resting.

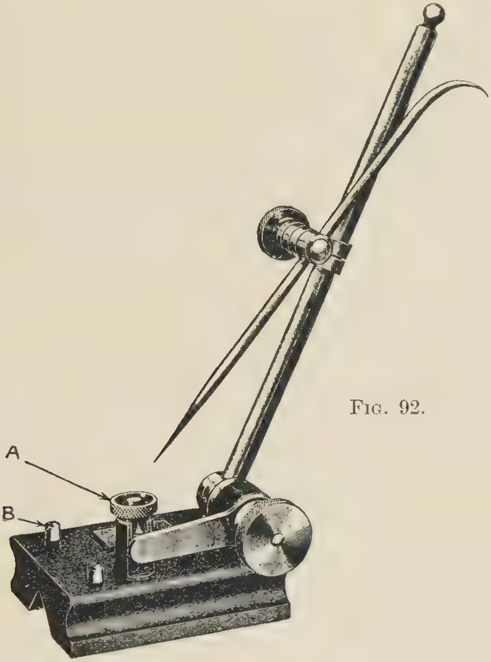


FIG. 92.

(iii) *Tools for Setting and Measuring Angles.*—The engineer's square is the commonest form of tool for testing angles. This

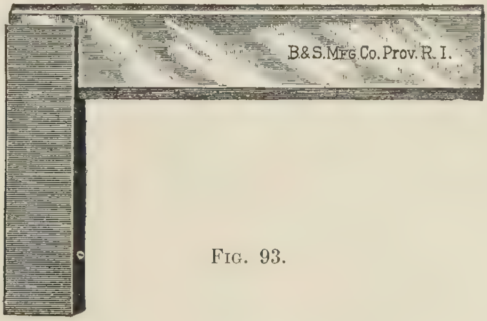

B&S.MFG.Co.Prov.R.I.

FIG. 93.

consists of a rectangular stock having straight sides, into one end of which the blade is fixed at right angles. For tool and gauge making, where the highest accuracy is required, it is an advantage to have the edges of the blade bevelled, as in Fig. 93. This enables small errors in squareness to be detected more readily by viewing against a well-illuminated background. Both the stock and blade of a square should be hardened to preserve their accuracy and prevent burring in use.* The type of square illustrated is made in a variety of sizes with blades from $1\frac{1}{2}$ to 6 inches in length. A similar type, but without bevelled edges, is obtainable up to 18 inches.

The various methods of testing angles other than right angles are dealt with in detail in Chapter VII., and it will suffice for the present purpose to mention only one form of workshop tool. This comprises a number of fittings which can be used in conjunction with an engineer's rule, Fig. 94. The one on the left is for scribing diameters on the end of a disc or shaft, and is therefore useful for centering, whilst that on the right serves for scribing or checking angles of either 90° or 45°. The central fitting is adjustable, and the inclination of its base to the straight edge is given by the scale of degrees engraved upon the part clamped to the rule.

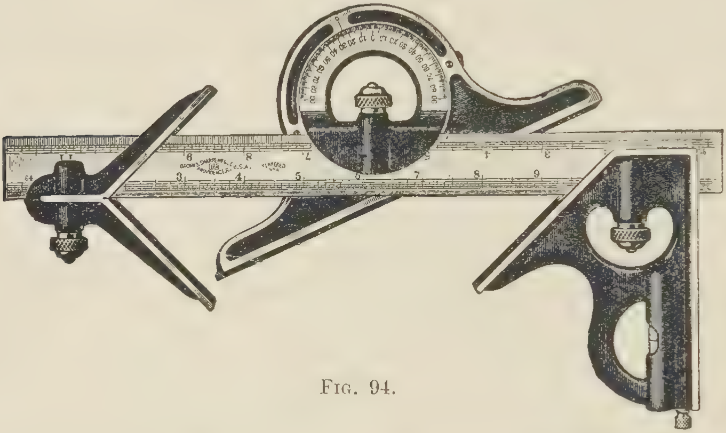


Fig. 94.

(iv) *Vices, Clamps and Setting-up Blocks.*—The types of small vice and clamp shown in Fig. 95 are used extensively by jig, tool and gauge makers for holding small parts together when machining. They also prove very useful for clamping straight edges, squares, etc., to surface plates, when measuring profile or position gauges.

The vice has a capacity of 2 inches, and is provided with two loose jaws of different thicknesses, either of which can be slipped over the rounded end of the screw to suit the size of the work. A vee-groove is cut along the base so that, when inverted, the vice can be used as a vee-block.

---

* For methods of testing the accuracy of squares, see p. 144 *et seq.*

The clamp shown on the right is made in a number of sizes with a maximum capacity of 3½ inches between the jaws. It may be mentioned that both the tightening screws are threaded through tapped holes in the upper jaw only. When in use, the inner screw is in tension and the outer one in compression, the rounded end of the latter resting in a recess near the end of the lower jaw.

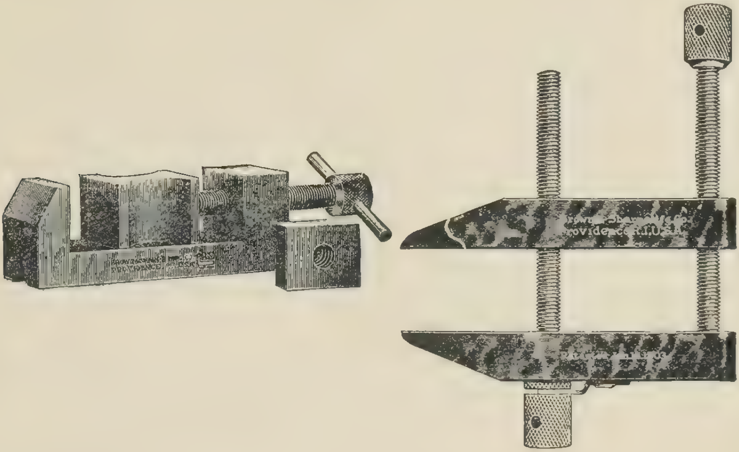


Fig. 95.

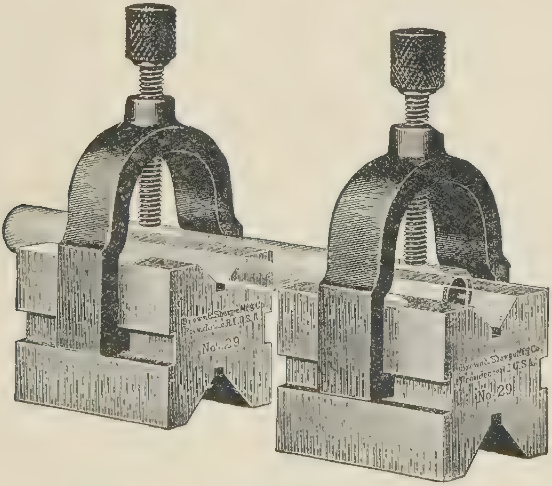


Fig. 96.

The hardened steel vee-blocks shown in Fig. 96 serve many useful purposes in both tool and inspection rooms. They are ground in pairs in order to ensure equality of size, particularly as regards the depth of the vee-grooves, which, in addition, are ground accurately midway between the sides. The blocks are approximately $1\frac{1}{4} \times 1\frac{1}{4} \times 1\frac{5}{8}$ inch, and the deeper vees will accommodate work up to $1\frac{1}{8}$ inch diameter. Specially designed clamps are provided for holding down cylindrical work, as shown.

When holding work in machine vices for milling, grinding, etc., it is often necessary to place packing beneath it in order to raise the upper surface above the jaws. Parallel strips of metal of various thicknesses are generally used for this purpose, but these can be replaced with advantage by the type of adjustable block shown in Fig. 97. This type of block, produced by Messrs. L. S. Starrett Company, operates on the principle of a pair of folding wedges ; the height can be readily adjusted to any desired figure within the available range by sliding one block on the other. The blocks are made in a number of sizes, the smallest of which has a capacity from $\frac{3}{8}$ to $\frac{1}{2}$ inch and the largest from $1\frac{3}{4}$ to $2\frac{1}{4}$ inches in thickness.

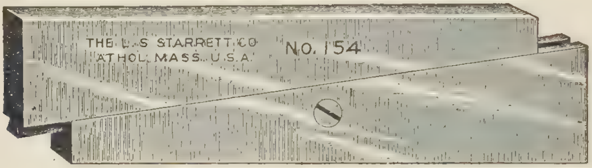


FIG. 97

Callipers, Dividers, etc.

The callipers and dividers shown in Fig. 98 are an improvement on the ordinary patterns, which are usually adjusted to the desired size by a hit-and-miss process of tapping the legs one way or the other. The Brown and Sharpe spring type illustrated are set to size by means of the screw and nut shown, the necessary constraint being provided by a stiff hoop-spring above the pivot. The adjusting screw is hardened to prevent wear, whilst, to facilitate rough adjustment, the nut is constructed on the principle of the spring chuck. Relieving the pressure on the nut by closing the legs together between the fingers causes the split jaws of the nut to open, enabling it to be slid freely on the screw to approximately the desired position. On releasing the legs, the pressure of the spring closes the nut on the screw ready for the final adjustment.

Large circles beyond the capacity of a pair of ordinary dividers can be scribed by means of trammels of the type shown in Fig. 99. By the addition of extension rods to the beam, diameters up to 54 inches can be dealt with. The legs can be clamped to the beam by the knurled nuts shown, and the upper part of the beam is flattened to prevent them turning. One leg is provided with a fine adjustment screw for accurate setting. The hardened scribing points are held in spring chucks, and, if desired, can readily be replaced by the pair of callipering points shown.

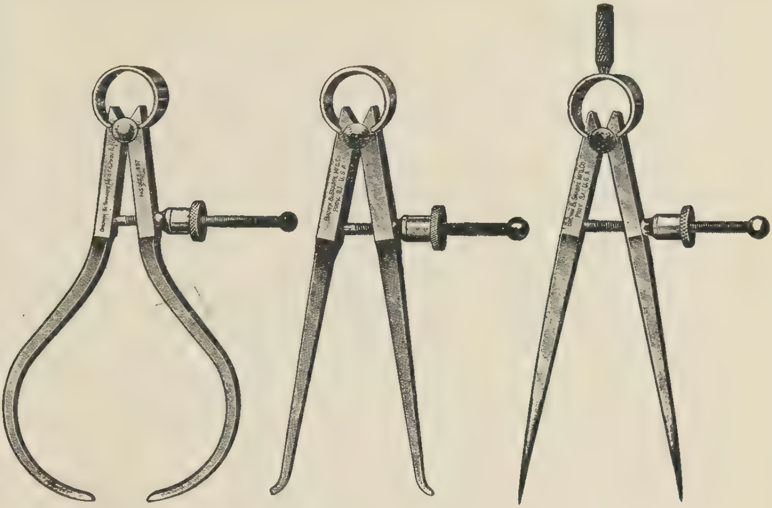


Fig. 98.

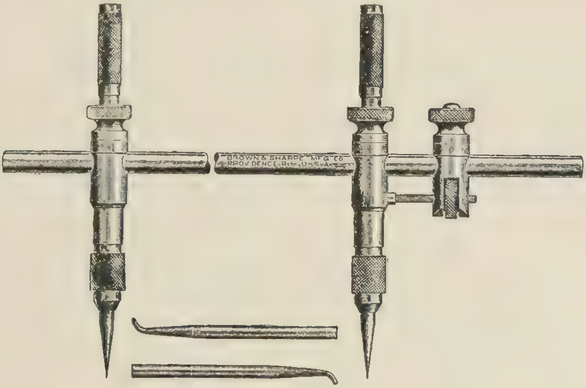


Fig. 99.

Thickness, Radius and Thread Gauges.

A set of thickness gauges, or "feelers", of the type carried by most fitters is shown in Fig. 100. The blades are of tempered steel and each is marked with its thickness in thousandths of an inch, the accuracy being within about a quarter of that unit. The thinnest blade is usually 0·0015 inch. These gauges are used chiefly for determining the widths of gaps which may exist between adjacent pieces of work by inserting the blades in the gap, in turn, until one is found to fit. Intermediate and larger sizes can be obtained by combining two or more of the blades. The particular type illustrated is made by Messrs. J. Chesterman and Co.

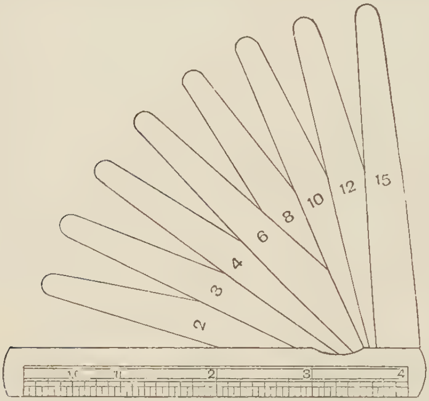


Fig. 100.

The checking of radii at the corners of jigs, etc., is facilitated by the use of a set of radius templates as illustrated in Fig. 101. Each template has an internal and external radius formed on it equal to the size engraved. The particular set shown increases in steps of $\frac{1}{64}$ inch from $\frac{1}{32}$ to $\frac{17}{64}$ inch radius. The method of application is shown in the two subsidiary diagrams.

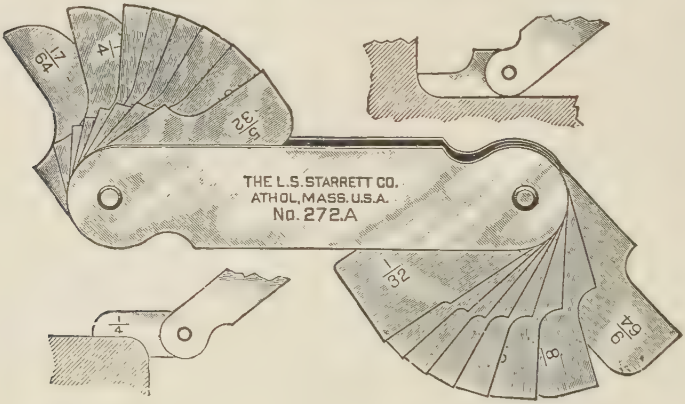


Fig. 101.

The number of threads per inch on a screw can be readily ascertained by matching it against one or other of the toothed blades of a screw pitch gauge, as shown in Fig. 102. The gauge illustrated has 22 blades corresponding to the usual pitches of the Whitworth thread within the range 4 to 48 threads per inch. These gauges are not intended as standards for thread profile or for use in determining errors in pitch, but only as a means of identifying the number of threads per inch. Similar sets are made for dealing with screws having other than Whitworth form, such as System International, U.S. Standard, etc.

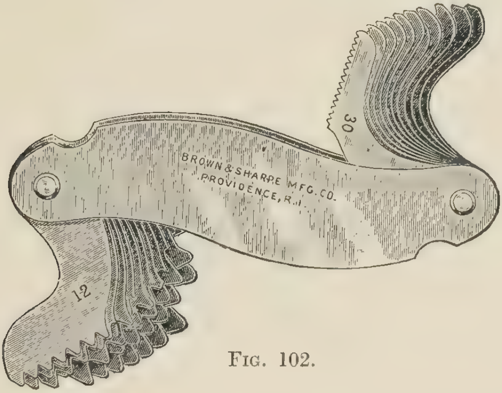

BROWN & SHARPE MFG. CO.
PROVIDENCE, R.I.
30
12

Fig. 102.

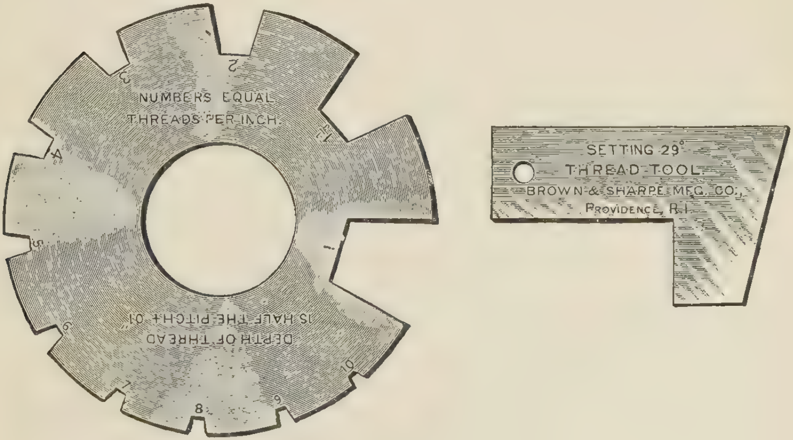


Fig. 103.

The circular gauge shown in Fig. 103 is for use in grinding threading tools for cutting Acme threads. Each of the gaps gives the correct profile for the nose of the tool to suit the designated number of threads per inch. Having ground the sides of the tool to the correct angle of 29°, the point is truncated until the nose is a light-tight fit to the corresponding gap in the gauge. The other plate is to assist in setting the tool square to the work. It is placed with its long edge against the spindle to be threaded, and the tool is adjusted until one of its flanks agrees with the sloping edge of the plate.

Wire and Plate Gauges.

It is the common practice to distinguish different sizes of wire or thicknesses of metal plate by "Gauge Numbers". Unfortunately the actual size corresponding to a given gauge varies with different systems. There are several systems of gauges in common use in this country, only two of which, however—the Imperial Wire Gauge system and the Birmingham Gauge system—have legal standing. These were authorized by Orders in Council in 1883 and 1914 respectively. Particulars of these systems, together with others in common use, will be found in Appendix I. p. 335.

The first of these systems is used mainly for wire; the largest size in it is No. 7/0 I.W.G., which corresponds to 0·500 inch, and the smallest No. 50 I.W G., which is equivalent to 0·001 inch. The Birmingham Gauge finds its chief application in the sheet-metal trade; the largest and smallest sizes are 15/0 B.G. and No. 52 B.G., corresponding to 1·000 and 0·00095 inch respectively.

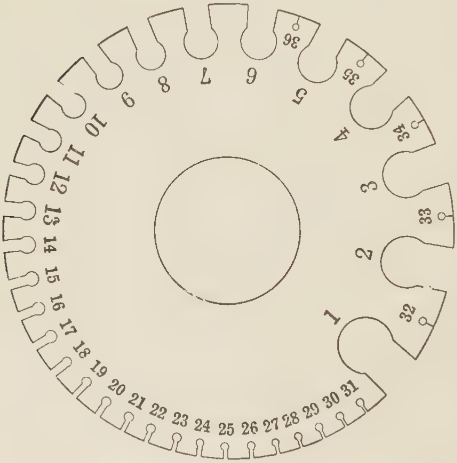


Fig. 104.

The common practice in ascertaining, or checking, the "gauge" of a sample of wire, or plate, is to test it with a "Wire Gauge" as shown in Fig. 104. These gauges generally take the form of either a circular or rectangular plate, having a series of gaps cut in the periphery with widths corresponding to the tabulated gauge sizes. To facilitate manufacture, the inner ends of the gaps are cleared by a larger-size drilled hole.

An improved form of wire gauge, as manufactured by Messrs. J. Chesterman and Co., is shown in Fig. 105. It will be seen that it is built up of three plates, the centre one having straight sides, whilst the outer ones are stepped. This arrangement not only facilitates accurate manufacture, especially of the narrower gaps, but enables the gauge of a wire to be determined much more readily by simply passing the wire down one or other of the four slots, and noting the gap at which it comes to rest.

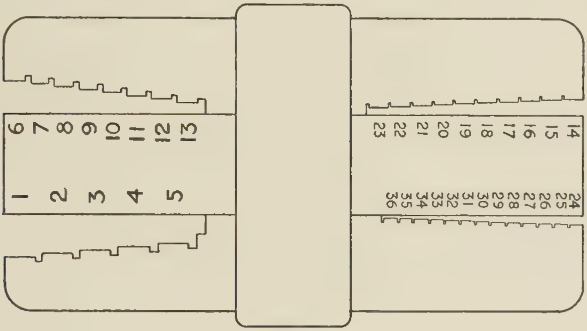


Fig. 105.

Although definite nominal sizes have been established for the two systems of wire and plate gauges mentioned above, no limits have been laid down for each individual size. The general practice of identifying a wire as the gauge number of the smallest gap which it will pass, clearly depends upon the maximum variations from nominal gauge size which can be allowed, and also upon the actual sizes of the gaps in the metal plate used. For example, a wire may be stated as being No. 20 I.W.G. (0·036 inch) because it will pass the No. 20 gap and refuse to enter the next smaller one, No. 21 (0·032 inch). Actually, the diameter of the wire might be 0·033 inch, which is obviously nearer the smaller size. Moreover, if the No. 21 gap in the plate happened to be somewhat undersize, a wire as small as even 0·032 inch might still be regarded as No. 20 I.W.G. if the above interpretation of these gauges is correct. Where the interval between consecutive sizes is a hundredth of an inch or more, it is hardly likely that a mistake would be made in deciding which was the nearer gauge for a particular wire. The difficulty occurs chiefly among the smaller sizes, where the intervals are of the order of only 0·001 inch, and, in some cases, only a tenth of that amount. For the smaller sizes, therefore, the gaps need to be extremely accurate in order to be of any use.

The trouble is met to some degree by the natural tendency for the gaps to be somewhat tapered and bell-mouthed. For example, wire which refused to enter one gap, but which would nearly pass through the next size larger, would probably be correctly identified as the gauge corresponding to the latter.

The author has met gauges in which each gap was definitely tapered from a width at the throat equal to the marked size up to the next size larger at the entrance. With a reasonably uniform taper, it then becomes a fairly simple operation to estimate the actual size of a wire from the distance it can be inserted into a particular gap.

The use of a continuous tapered slot for gauging wire diameters is illustrated by the gauge shown in Fig. 106. The slot is actually about 7 inches in length, and has one edge graduated into thousandths of an inch from zero up to 0·250 inch. The plates forming the slot are hardened to resist wear.

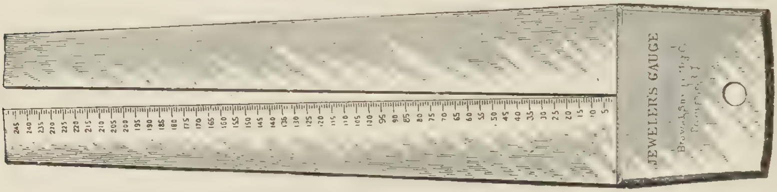


FIG. 106.

The perforated gauge in Fig. 107 is a type frequently used by mechanics and store-keepers for identifying the sizes of drills and round stock. The example illustrated covers the range from $\frac{1}{16}$ to $\frac{1}{2}$ inch by steps of $\frac{1}{64}$ inch. In another pattern, the holes are sized and numbered in accordance with the practice generally recognized in connection with twist drills (see table p. 336).

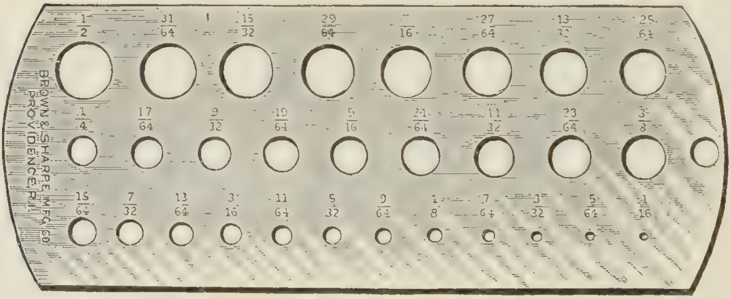


FIG. 107.

Test Indicators.

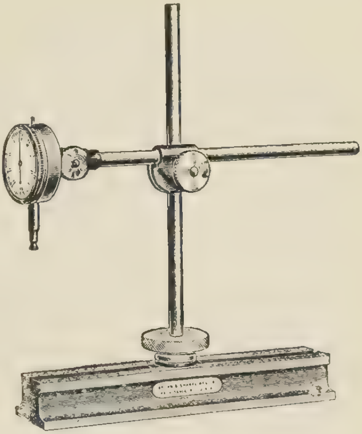


FIG. 108.

The dial test indicator, one of the many forms of which is illustrated in Fig. 108, is a valuable tool both to the mechanic when setting up work preparatory to machining, and to the inspector. It consists essentially of an indicator, movements of the spindle of which are recorded by a pointer on a dial, graduated usually to 0·001 inch.* The indicator is attached to a rod which can be either clamped to the tool holder of the machine or supported on the pillar of a suitable base, as shown. The position of the indicator is capable of adjustment in all directions with respect to the base.

Depth Gauge.

Certain types of depth gauges have already been described in connection with micrometers and scale measurements.† The particular form of the instrument shown in Fig. 109 was designed by

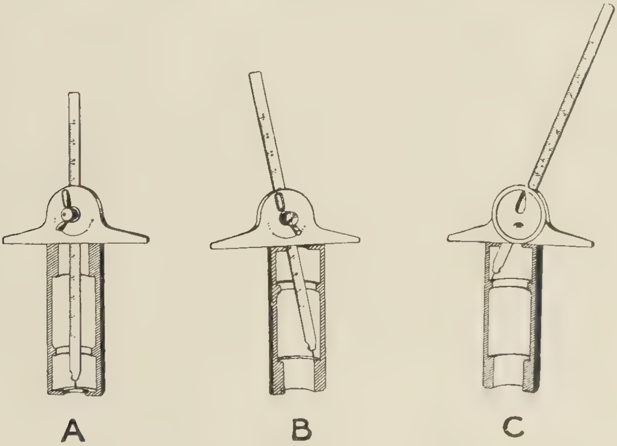


FIG. 109.

---

* There are many patterns and makes of these indicators, some of which have been described in Chapter XVIII. of vol. i.

† See pp. 52 and 70.

Messrs. Carl Zeiss, and is of interest as it enables depth measurements to be made in positions inaccessible to the ordinary pattern.

The blade, furnished with a rounded feeler point at the lower end, is housed in a slot in the stock, and can be clamped either vertically, as at A, or in one or other of two sloping positions, B and C. The blade has three scales, one for each position ; they are so graduated that in each case the reading gives a direct measure of the vertical distance of the measuring point below the base of the instrument. The fiducial marks on the edge of the viewing slots are arranged to avoid any confusion as to the correct scale to be used for each position of the blade.

Optical Drill Gauge.

An optical instrument has recently been introduced by Messrs. Carl Zeiss for inspecting the cutting ends of twist drills, with the object of ascertaining whether the end has been ground symmetrically about the axis, since an error in this respect causes a drill to cut too large a hole.

The drill to be tested is laid in a vee-groove, Fig. 110, and its end inspected by a magnifying glass carried in the tube to the left. The ocular is provided with a graticule, and the appearance in the eyepiece is indicated in the lower part of the figure.

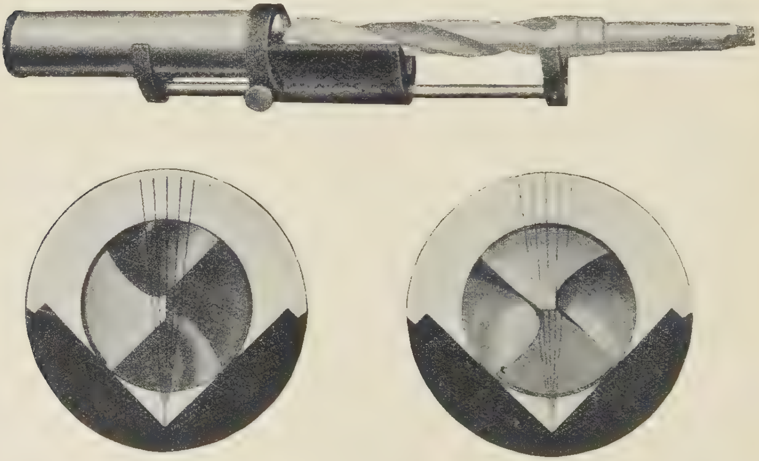


FIG. 110.

In the left-hand diagram the drill has been arranged in order to test whether the junction line of the two ground portions is central. On turning the drill through 90°, the sloping lines on the graticule on each side of the central one indicate whether the point is symmetrical in the other direction.

The appliance is made in four sizes, the smallest being suitable for drills up to $\frac{1}{8}$ inch, and the largest for drills between $1\frac{3}{16}$ and 2 inches.

ADDITIONAL REFERENCE FOR CHAPTER IV

"Development of Measuring Devices Primarily Manual," *Amer. Mach.*, vol. 69. p. 686 (1928).

CHAPTER V

MEASUREMENT OF TAPER, FORM AND POSITION GAUGES

The measurement of ordinary plug cylindrical limit gauges presents no difficulty in either the workshop or the inspection room. Their diameters can readily be ascertained by comparison with standard discs or block gauges with the aid of a micrometer, measuring machine, or one of the many well-known forms of " Indicators ".* Similarly, plain rings and snap gauges can be dealt with by means of block gauges or by one or other of the methods described under the heading of " Internal Measurements ".†

In addition to these simple gauges, there are many others which may be broadly separated into two types :

I. Form Gauges.

II. Position Gauges.

The first group includes conical plugs and rings, plates with tapered edges and others whose profiles consist of straight lines and curves. Position or assembly gauges are used for checking the relative positions of different parts of a piece of work, such as the spacing of holes or their position with relation to certain edges or faces. Such gauges are frequently met with in munition work, especially in connection with fuses. In this class may also be included spline and castellation gauges, used for checking the positions of keys and serrations on shafts and in hubs.

It is impossible in the space available to deal with the measurement of more than a few typical cases of form and position gauges. The examples chosen, however, should suffice to illustrate the general principles of the methods, which can be adapted with a little thought to suit any particular gauge.

It will be seen later that practically every measurement of this kind involves the use of accurately ground cylinders or balls, up to about an inch in diameter, in conjunction with the familiar sets of block gauges. In this connection it may be useful to refer to the

---

* See Vol. I. Chapter XVIII.

† See Chapters VIII. and IX.

Hoffmann Roller Gauges, a set of which is shown in Fig. 90, Vol. I. p. 121. These gauges consist of hardened steel rollers such as are used in bearings. The ends are flat, and each roller is ground so as to be equal in length and diameter, both dimensions being correct to within ±0·0001 inch. A set of these roller gauges comprises 16 pieces, ranging in size from $\frac{3}{16}$ to $1\frac{1}{4}$ inch. Their shape and range of sizes render these gauges extremely useful for surface plate work. Generally two of one size are required, so that a duplicate set becomes almost essential.

It should be mentioned that whilst these gauges can be used with every satisfaction as end standards for setting up micrometers and measuring instruments, their tendency to develop a lobed shape* in the grinding of the cylindrical surface necessitates caution when using them for purposes where true cylindricity is essential, such as checking the sizes of holes, or in certain cases of form gauge measurement. The suitability of any particular roller for these purposes can be easily tested by rotating it in a vee-block under an indicator. This method reveals the presence of any lobing: if the variation recorded by the indicator is within 0·0001 inch, the roller can be accepted as sufficiently cylindrical for use in all ordinary measurements of this kind.

Taper Plug Gauges.

The most satisfactory method of testing taper plug gauges both for angle of taper and diameter is by the use of slip gauges and a pair of roller gauges, as shown in Fig. 111. The gauge is stood on a surface plate and, if necessary, is held down by a clamp screw fixed in a suitable bracket fastened to the plate. A pair of cylinders, or roller gauges, whose diameters are known accurately, are placed at the base of the gauge, as shown in the diagram. The distance M_1 over the outsides of the rollers is carefully measured with a micrometer. This measurement is repeated across different diameters round the gauge, and the two rollers are then raised on equal piles of slip gauges of height H, as shown by the dotted lines, and a further measurement M_2 is made. The height of the piles of slip gauges can be altered to bring the rollers to as many positions as is thought desirable. Measurements are made at each position in turn, and are noted together with the corresponding heights of the two piles of slip gauges.

The best procedure in working out the results is to take the standard drawing of the gauge, and, from the dimensions given, to calculate the theoretical measurements across the rollers at the various heights used. The calculation is of a simple nature. Suppose

---

* See Vol. I. p. 122.

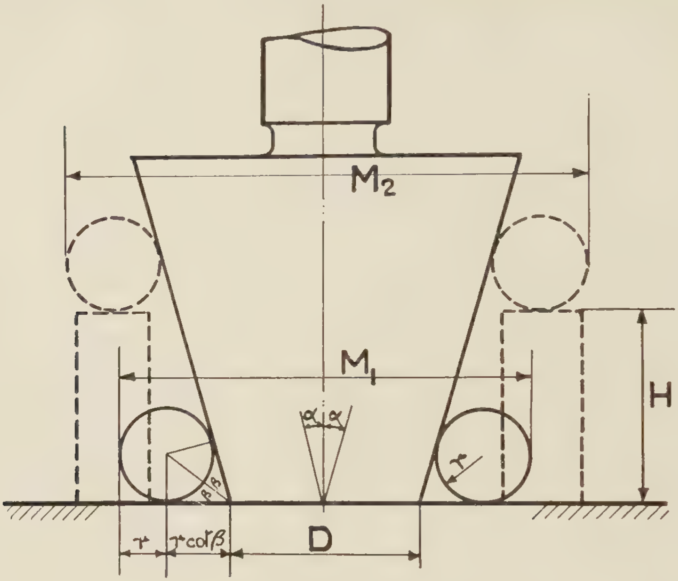


FIG. 111.

the diameter of the base of the gauge is given as D, and the semi-angle of taper as a, then, if the radius of the rollers is r, we have

$$M_1 = D + 2r(1 + \cot\beta),$$

where $\beta = \frac{1}{2}(90^\circ - a)$. Similarly

$$M_2 = D + 2r(1 + \cot\beta) + 2H\tan a.$$

As an example, the table below gives a series of measurements made on a taper plug gauge, together with the corresponding calculated values of the distance across the rollers as obtained from the above formulae :

Height H.	Distance across Rollers.		Error in Size.
	Measured.	Calculated.	
0·0″	1·7430″	1·7428″	+0 0002″
0·25	1·7680	1·7678	+0·0002
0·5	1·7931	1·7928	+0·0003
0·75	1·8182	1·8178	+0·0004
1·0	1·8434	1·8428	+0·0006
1·25	1·8686	1·8678	+0·0008
1·5	1·8938	1·8928	+0·0010

The last column gives the error in the diameter of the gauge at the various sections at which the rollers made contact with it. It will be noted that these errors are larger towards the upper end of the gauge where the height H is greatest, and moreover, the error towards the centre is less than the mean of the errors at the extremities. This indicates that the general rate of taper is too great, *i.e.* the angle is too large, and also that the conical surface is slightly hollow towards the centre. The latter error could be checked by laying the gauge on a lapped surface plate, when a slight gap of about 0·0001 inch should be noticeable at the middle against a strong light.

To facilitate tests of this description, and to enable the diametral measurements to be made with block gauges instead of a micrometer, an arrangement such as is shown in Fig. 112 can be used. The gauge is placed between two parallel plates fixed to the sides of a cast-iron base block. Knowing the separation of the side plates, the dimension over the cylinders is obtained by gauging the distances between the cylinders and the plates as shown.

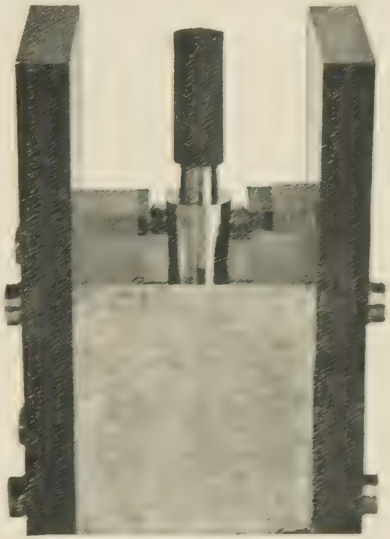


Fig. 112.

This arrangement is due to the Pitter Gauge Company.

Taper Ring Gauges.

A common method of testing taper ring gauges in the workshop is by the use of a corresponding taper plug gauge, of known accuracy, as a check gauge. The two gauges should assemble, and either the shoulder of the plug, or a line scribed round its surface, should come flush with the upper surface of the ring. This method is liable to lead to erroneous results unless special care is used. Fig. 113 shows three ring gauges having faulty tapers which could be carelessly passed as "fitting" the same check plug. The errors in the tapers of the rings are, of course, exaggerated. If the actual errors were large they could be detected by the presence of play between the gauges. Such errors could also be detected to within fairly fine limits by the use of some form of marking material applied *very thinly* to the plug gauge before inserting it in the ring, and noting to what extent it became removed after rotating the plug. For testing a ring to an accuracy of an order of ± 0·0001 inch, however, it would be necessary to resort to direct measurement.

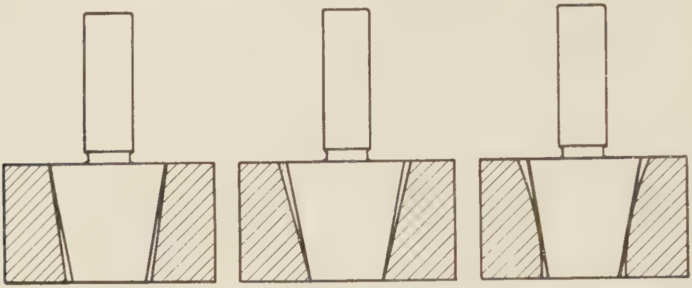


Fig. 113.

The general method of measuring the rate of taper and the diameter of a taper ring gauge is by the use of steel balls. When the minimum diameter of the gauge is above $1\frac{1}{2}$ inches or so, the method shown in Fig. 114 can be used. The scheme is analogous to that already described and illustrated in Fig. 111 for the measurement of taper plug gauges, the rollers being replaced by a pair of steel balls, the distance between which is measured by means of slip gauges. The balls are first placed on the surface plate, and are afterwards raised on equal piles of gauges to various heights in succession. The calculation of the results is similar to that explained in the case of the plug gauge above.

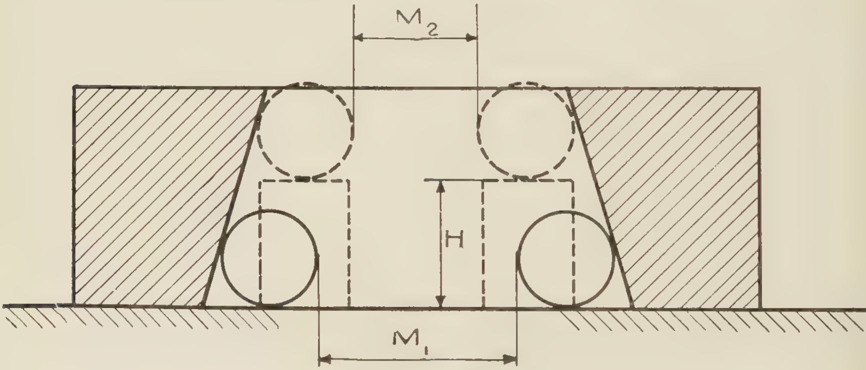


Fig. 114.

For smaller sizes of rings it is not possible to insert the slip gauges, and single balls of different sizes are used in turn, as shown in Fig. 115. The balls are allowed to rest in the cone of the ring, and the distance from the top of the ball to the upper surface of the gauge is measured with a depth gauge, or, if the ball protrudes, by means of slip gauges. As Hoffmann steel balls are made in $\frac{1}{32}$nd sizes from 1 inch to $\frac{1}{2}$ inch, and below that size in $\frac{1}{64}$th inch steps, it is usually possible to select several sizes of balls which will suit any particular ring.

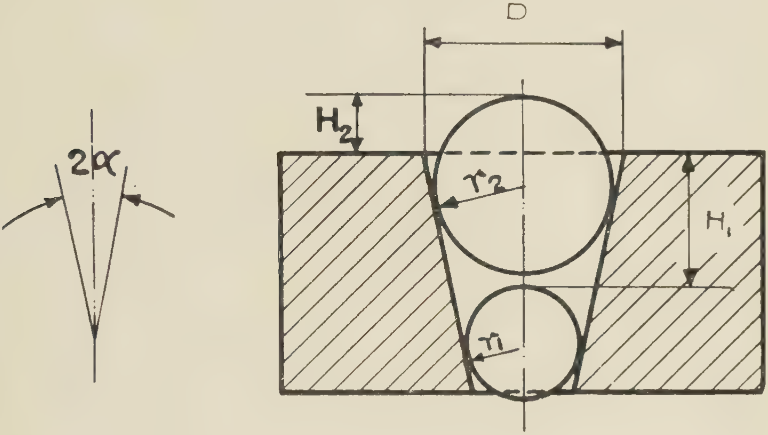


FIG. 115.

Referring to Fig. 115, if the total angle of the cone be denoted by $2a$, we have :

$$\operatorname{cosec} a = \frac{H_1 + H_2 + r_1 - r_2}{r_2 - r_1}.$$

Also the diameter D at the upper surface is given by :

$$D = 2[r_2 \sec a + (r_2 - H_2) \tan a].$$

It should be noted that, by this method of measuring distances along the axis of the cone, the diameter of the ring is obtained to an enhanced accuracy according to the fineness of the taper.

In some cases where the angle of taper is very slight, it is not possible to find more than one size of ball which will rest in the cone. For such gauges the method indicated in Fig. 116 may be adopted. A ball somewhat smaller than the minimum diameter of the ring is chosen, and this is inserted together with a small cylinder D_1 of suitable size, so that the ball rests near the bottom of the ring. After measuring the height H_1, the cylinder is changed for another of larger diameter D_2, so as to bring the ball higher in the gauge. The standard wires used in the measurement of the effective diameters of screws are very useful for this purpose, as in a complete set they differ consecutively by only a few thousandths of an inch. In special cases it may be necessary to grind and lap suitable cylinders, but that is a fairly easy matter.

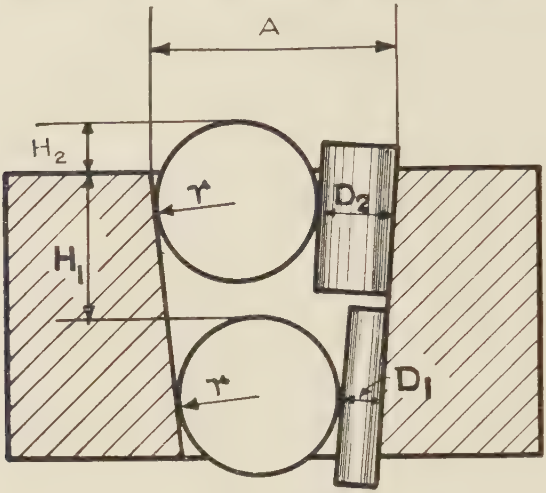


FIG. 116.

In the arrangement in Fig. 116, it can be readily shown that if a be the semi-angle of the cone,

$$\sin a = \frac{D_2 - D_1}{2(H_1 + H_2)},$$

and the diameter A at the upper surface is given by :

$$A = (2r + D_2) \sec a + 2(r - H_2) \tan a.$$

Taper Plate Gauges.

These are measured by the use of roller gauges and block gauges in practically the same manner as described for taper plug and ring gauges. Instead of standing the gauges on the surface plate, however, they are placed flat downwards; in the case of the internal tapers, roller gauges are used instead of balls.

If a number of taper plates having the same angle have to be measured, the method shown in Fig. 117 is sometimes adopted. Two templates, T, T, fastened together with dowel pins, are ground up on all four edges so as to have the correct angle of taper. This angle can be tested by taking measurements over rollers when the square edges of the templates are placed in contact, as shown at B. Having obtained the correct angle, the templates are then measured when arranged as at C, thus obtaining the dimension *m*. The two pieces are then placed one on each side of the gauge G, to be tested, as shown at A, and measurements M are made at the top and bottom. If the outer edges are found to be parallel, the taper of the gauge agrees with that of the template; also, the distance across the gauge in the position half-way down is given by (M – *m*), and this can be compared with the corresponding drawing dimension.

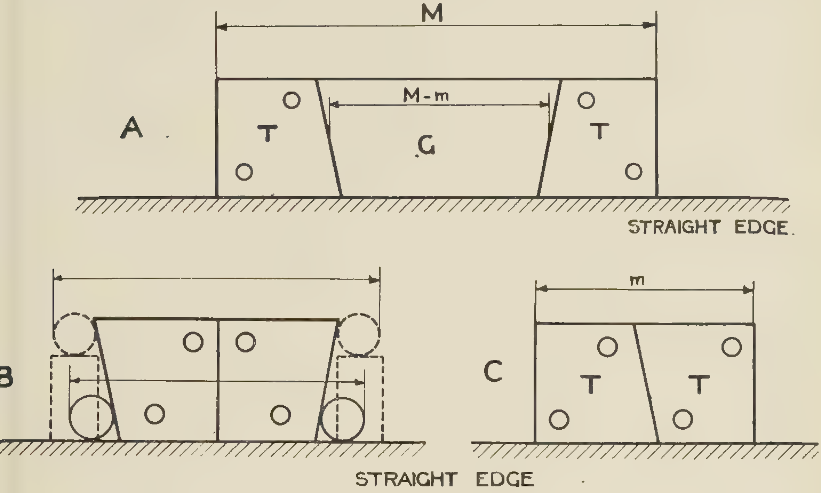


Fig. 117.

Such templates can also be used for checking internal taper plate gauges by measuring the distance between the parallel edges with slip gauges.

Profile Gauges.

The smaller sizes of profile gauges, such as radius templates, are most readily checked by one of the following optical methods :

(i) Optical projection of an image of the profile on to a screen at a definite magnification, and comparison of this image with an enlarged drawing.

(ii) The gauge is mounted on a table whose position, in rectangular co-ordinates, is controlled by micrometer screws, and different parts of its profile are viewed in turn through a fixed microscope fitted with cross-wires, the movements of the gauge being measured on the micrometers.

Descriptions of machines for carrying out measurements by these two methods will be found in Chapters VI. and XI.

(iii) *By the use of a Check Gauge.*—Another method of testing profile gauges is to have a check gauge or counterpart of the gauge, and to try the fit of the two pieces when placed together on a sheet of glass in front of a strong light. Differences between the two edges in contact can be readily detected, especially if the gauges are made of fairly thin plate, but it is not easy to state the amount of these differences. This method is mostly used in the workshop during the manufacture of the gauges, and it is the aim of the mechanic to adjust the profile of the gauge until it is a "light-tight" fit to the check. The check itself must be accurate, and should first be verified by optical projection and, if necessary, adjusted until its profile matches the enlarged drawing exactly.

An example of such a check gauge is shown in Fig. 118. Although complicated in form, the production of this check should present little difficulty if a projection apparatus and the corresponding enlarged drawing are available.

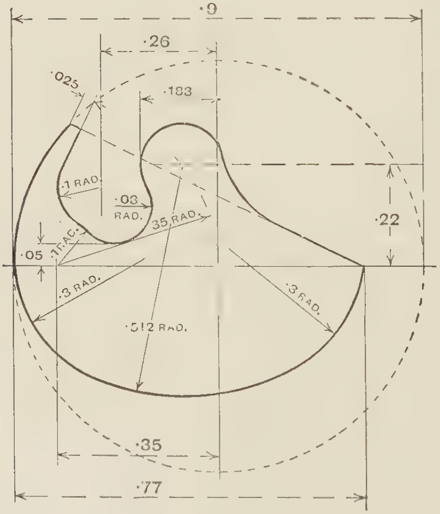


Fig. 118.

Larger form gauges, which very often have symmetrically curved edges, can be dealt with by the use of slip gauges and roller gauges. A form of gauge frequently met with on shell work is shown at A in Fig. 119, whilst the corresponding check gauge is shown at B in the same figure. If such a check gauge is available, the gauge can be readily tested by trying the fit of the two together. In any case it is necessary to verify the accuracy of the male check piece, and, in addition to trying the fit of the check, it is often desirable to ascertain the actual amount of the errors in the gauge itself should the fit be imperfect. A method of measuring the two pieces is indicated in the figure; it will be noted that the principle is practically the same as that used in the measurement of taper gauges. In the case of the female gauge, the distances between the rollers, when placed on various equal piles of blocks, are measured with block gauges:

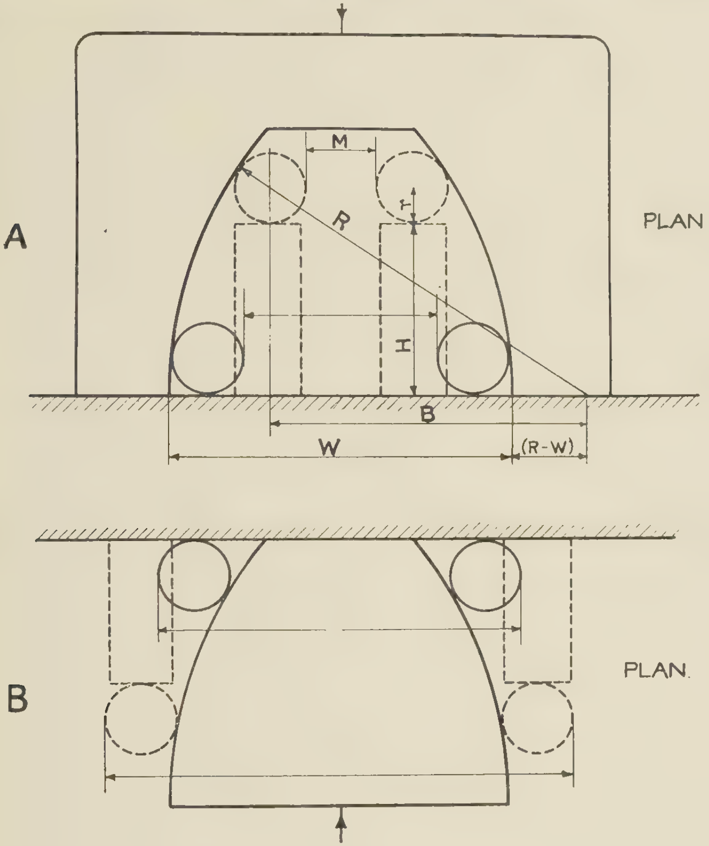


Fig. 119.

for the check piece, the distances over the rollers are measured with a micrometer.

The calculation of the theoretical distances from the drawing dimensions of the gauge is simple.

In the case of the female gauge we have,

$$B = \sqrt{(R - r)^2 - (H + r)^2},$$

and M, the theoretical distance between the rollers, is given by

$$M = 2B - 2R + W - 2r.$$

If both gauge and check are available, their symmetry can be checked by trying them together in both positions. The symmetry of each piece can also be tested independently by taking diagonal measurements between or across a pair of rollers, one resting against the straight-edge and the opposite one standing on the pile of gauges.

Position Gauges.

This type of gauge is most easily tested by means of check gauges. The check gauge is an accurate replica of the piece of work to be tested, but is made in such a form as to be capable of being measured with as little difficulty as possible. The check for the gauge shown in Fig. 31, p. 22, would be of the form shown in Fig. 120. The verification of such checks for position gauges usually involves a considerable number of measurements. The various steps in the process for this particular check would be as follows :

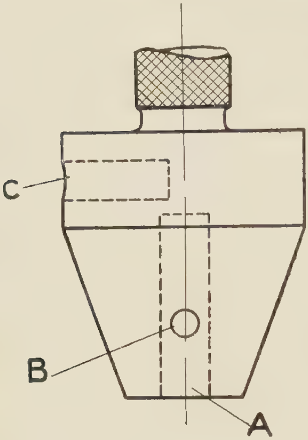


Fig. 120.

(*a*) Measure tapered portion of body, using method shown in Fig. 111, p 90. Measure parallel part with micrometer. Test concentricity of the two parts.

(*b*) Check diameters of holes A, B and C by measuring the diameters of plugs which fit them.

(*c*) Test whether hole A is truly axial as at (*a*) in Fig. 121. The block of gauges marked J. G. should be equal to the difference between the radii of the parallel part of the body and of the plug in hole A.

(*d*) Test whether axes of holes B and C pass through axis of body as at (*b*) in same figure. (Only test for hole B shown.)

(*e*) Test parallelism of holes B and C with base, and their heights as at (*c*). (Only test for hole C shown.)

(*f*) Test right angle between pins B and C in plan as at (*d*).

The above case is fairly simple, as the only angle which has to be measured between the axes of the holes happens to be a right angle. A rather more difficult gauge is shown at (*a*) in Fig. 122, which also shows the various dimensions to be tested. The method of testing the offset of the pin and the angle of the slot in relation to it is shown

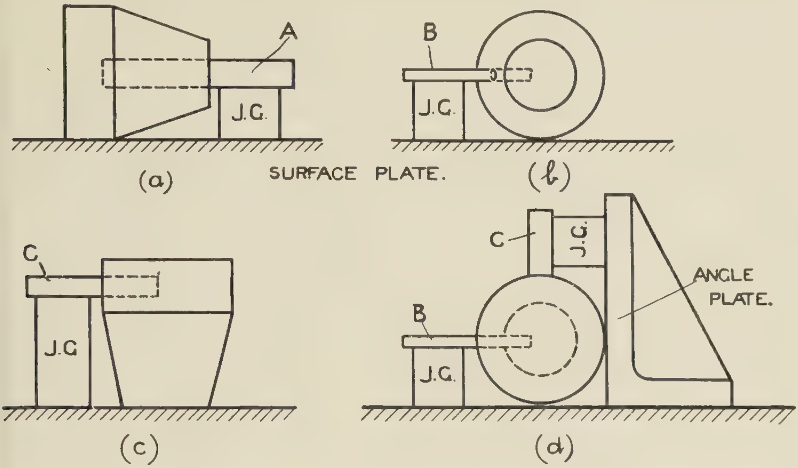
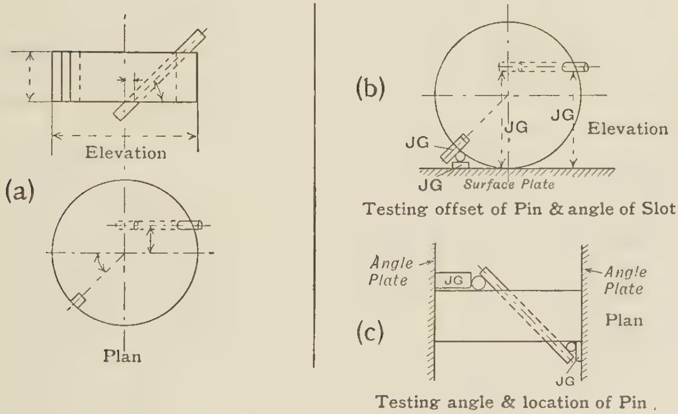


Fig. 121.



Testing offset of Pin & angle of Slot

Testing angle & location of Pin.

Fig. 122.

at (*b*) in the same figure. The angle of the pin with reference to the flat faces of the gauge is measured by the method shown at (*c*).

Spline Gauges.

The most important test on spline gauges is the verification of the equality of spacing of the splines or slots. A pair of 4-way spline gauges is shown in Fig. 123, together with an indication as to how this test can be carried out. In the case of the plug, the symmetry can be tested by placing cylinders or roller gauges in the angles of adjacent pairs of splines in turn, and measuring the distance between them with block gauges, as at (*a*). A similar method can be used for the ring gauge, after fitting block gauges to the slots, as shown at (*b*).

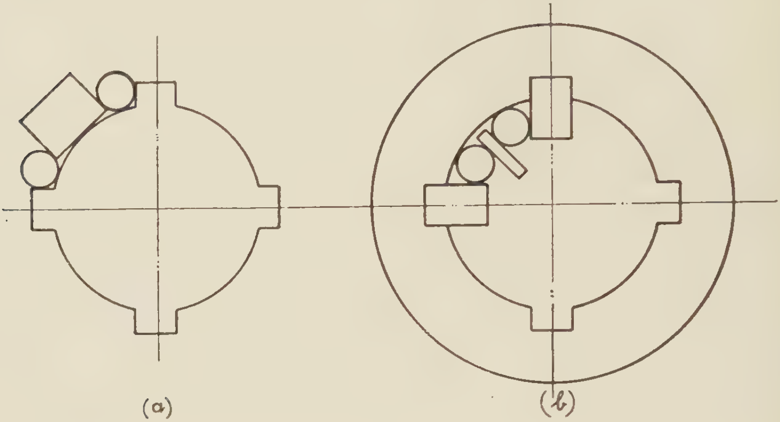


FIG. 123.

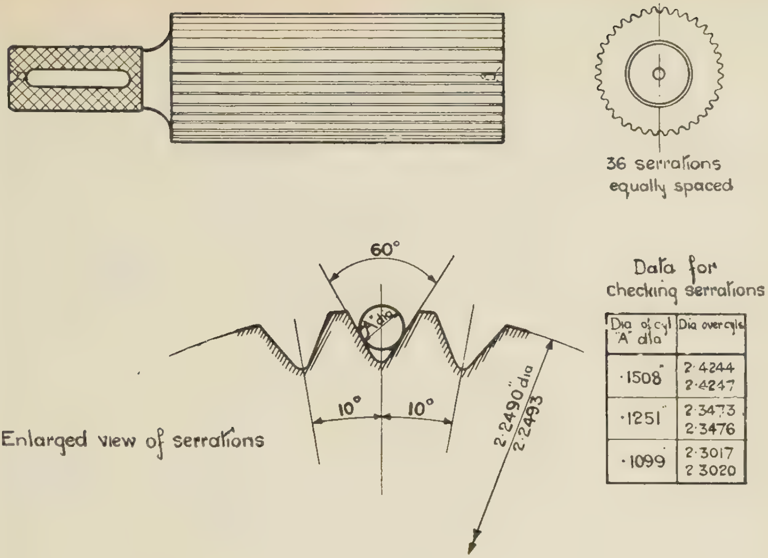
After verifying the widths and heights of the splines and slots in the usual manner, the symmetry of the gauges can be finally checked by assembling them in all possible positions and noting the fit in each case.

Castellation Gauges.

A similar kind of problem arises in the case of castellation gauges used for checking the serrations on the propeller shaft and hub of aero-engines. The male gauge usually consists of a hardened steel plug with a number of equally-spaced vee-grooves ground along its surface, as shown in Fig. 124. The tests upon such a gauge should cover the following points :

(*a*) Angle and depth of grooves.
(*b*) Parallelism of grooves with axis of gauge.
(*c*) Equality of spacing of grooves.
(*d*) Outside diameter.

The angle of the grooves and the diameter of the imaginary cylinder upon which their apices would lie can be found by taking diametral measurements over two pairs of small cylinders placed, in turn, in opposite grooves of the gauge. The diameters of the cylinders should be chosen so that they make contact well towards the upper and lower ends of the flanks of the groove.



Dia of cyl "A" dia	Dia over cyls
·1508"	2·4244 2·4247
·1251"	2·3473 2·3476
·1099"	2·3017 2 3020

FIG. 124.

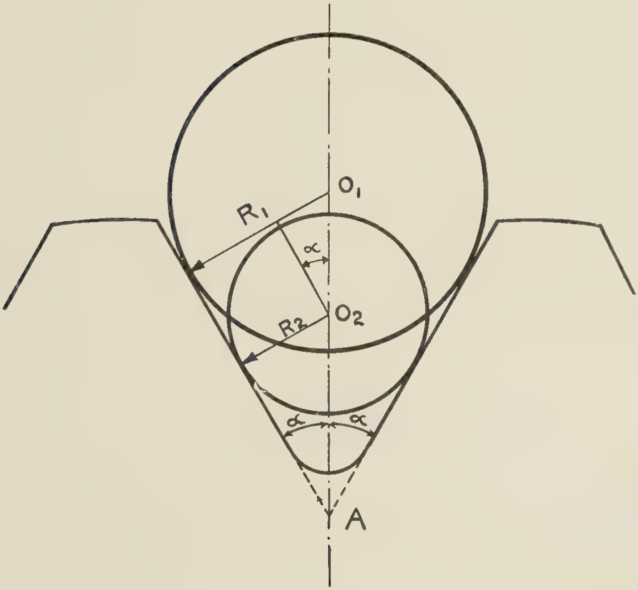


FIG. 125.

If M_1 and M_2 represent the measurements over pairs of cylinders of radii R_1 and R_2 respectively, the distance between their centres, $0_1 0_2$, Fig. 125, is given by

$$0_1 0_2 = \tfrac{1}{2}(M_1 - M_2) - (R_1 - R_2),$$

$$\therefore \sin a = \frac{R_1 - R_2}{0_1 0_2} = \frac{R_1 - R_2}{\frac{1}{2}(M_1 - M_2) - (R_1 - R_2)}.$$

The radial distance to the apex of the groove A is equal to

$$(\tfrac{1}{2}M_1 - R_1) - R_1 \operatorname{cosec} a,$$

which reduces to

$$\frac{R_1 M_2 - R_2 M_1}{2(R_1 - R_2)}.$$

The straightness of the flanks can be judged by taking a measurement over a third pair of cylinders with diameters about midway between the other two, and comparing the measurement obtained with that calculated from the values found for a and the radius to the apex A.

The root diameter of the groove can be measured with the aid of small steel prisms such as are used in screw thread measurements. This measurement and that described above can be made most conveniently in a " floating-micrometer " type of machine such as is described later under screw thread measurements.

To test the parallelism of the grooves with the axis of the gauge, it is mounted on centres and an indicator traversed along one flank of a groove from end to end.

The spacing of the grooves cannot be tested to sufficient accuracy by comparing the measurements over a pair of cylinders placed in adjacent grooves round the gauge. One method of obtaining a satisfactory test is to place the gauge between centres with a finely graduated circle, such as is fitted to theodolites, coupled to it. The gauge is then indexed round against a stop which fits into each groove in turn, and at each position readings are obtained on the circle by a pair of verniers, or low power microscopes, situated at the ends of a diameter, so as to eliminate any eccentricity in the mounting of the circle.

Another method, and one which is used at the National Physical Laboratory, is to mount the gauge between the centres of a gear measuring machine.* The gauge can then be rotated time after time through an angle, which is repeated to a high degree of accuracy at each step, and which is made slightly greater or less than the nominal angular spacing of the vees. After each rotation, a special pantograph is used to obtain a trace on a smoked plate of each space as it arrives in position, and, by examination of the combined trace of all the spaces in a projection apparatus to a magnification of 50 times, it is possible to plot a curve of spacing errors for all the spaces. This method can be relied on to an accuracy of 0·0001 inch.

---

* See Chapter XVI.

Such a curve, obtained in the manner indicated, on a gauge having 36 grooves, is shown in Fig. 126. With the exception of two high points, the centre lines of all the grooves or spaces are correctly situated to within ±0·00015 inch. The abnormal errors at the 13th and 21st spaces were found to be due to metal missing from one flank of the adjoining tooth, and, as this would not affect the general functioning of the gauge, these errors had no significance.

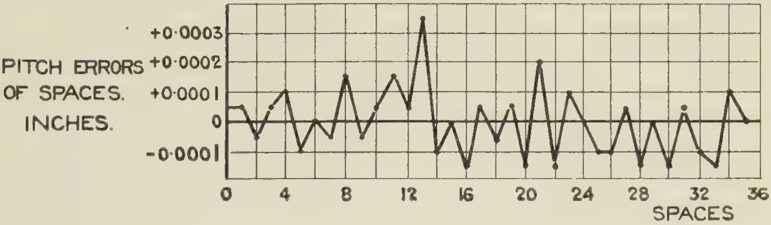


FIG. 126.

Female serration gauges can be tested on the same lines as the male gauges. To examine the spacing, the gauge can be mounted on an arbor inserted only part of the way through the ring, so as to leave the serrations accessible for tracing towards one end.

Since serration gauges are usually manufactured in pairs, a final test can be carried out by assembling them in a number of different positions.

Plate Gauges with Large Radii.

Tests are sometimes required on plate gauges in the form of male, or female, templates for large radii. These can be dealt with by a cylinder and block gauge method as indicated in Fig. 127. The curved edge of the plate G is pressed gently into contact with two cylinders resting against a good straight-edge which is clamped down to a surface plate. The cylinders are maintained in position by suitable blocks, clamped to the surface plate in the positions shown, and their centre distance L is determined by measurements taken either between, or across, the cylinders. The distance h, or h', between the straight-edge and the middle point of the curved edge

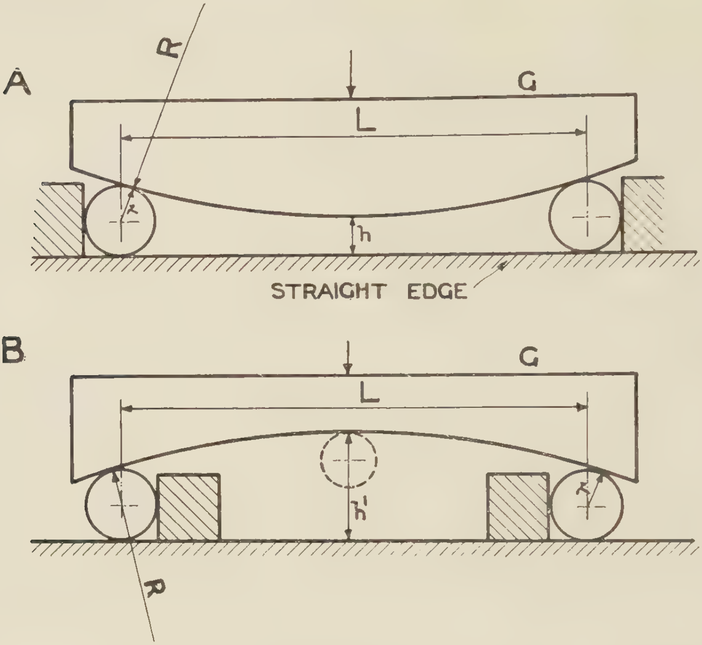


FIG. 127.

is then measured with block gauges, together with another cylinder in the case of the female radius.

In diagram A we have :

$$\frac{L^2}{4} = (2r - h)\{2(R + r) - (2r - h)\}.$$

Whence,
$$R = \frac{L^2}{8(2r - h)} - \frac{h}{2}.$$

Similarly, for the female radius in diagram B :

$$\frac{L^2}{4} = (h' - 2r)\{2(R - r) - (h' - 2r)\}.$$

Whence,
$$R = \frac{L^2}{8(h' - 2r)} + \frac{h'}{2}.$$

If it is desired to check the uniformity of the radius in different positions along the plate, the spacing L between the cylinders is reduced, and any variations in the distance h noted as the plate is moved past the cylinders, which are maintained at a constant distance apart.

ADDITIONAL REFERENCES FOR CHAPTER V

"Splines and Serrations," H. T. Wright, *Machinery*, vol. 27, p. 257 (1925).

"Making Inserted Spline Gauges," F. F. Swallow, *Machinery*, vol. 17, pp. 613, 768 (1921).

"Female Spline Gauges," *Machinery*, vol. 27, p. 215 (1925).

"Gauging Splined Shafts," S. H. Bailey, *Amer. Mach.*, vol. 66, p. 302 E (1927).

"Manufacture and Fits of Splined Sliding Gears and Clutches," G. Doorakkers, *Amer. Mach.*, vol. 56, p. 37 E (1922).

"Gauging Tapers," C. C. Jensen, *Amer. Mach.*, vol. 66, p. 300 E (1927).

"Taper Gauges," H. M. Funnell, *Amer. Mach.*, vol. 56, p. 184 (1922).

"Taper Gauges," H. T. Wright, *Machinery*, vol. 26, p. 233 (1925).

"Form Grinding of Circular Form Tools," E. Sheldon, *Amer. Mach.*, vol. 68, p. 1052 (1928); vol. 69, p. 8 (1928).

"Accurate Grinding of Profiles of Small Form Cutters," *Jour. Sci. Inst.*, vol. 5, p. 260 (1928).

"Inspecting Large Radius Gauges," *Machinery*, vol. 27, p. 754; vol. 28, p. 92 (1926).

"Profile Curvature Gauge," W. Souder, *Amer. Mach.*, vol. 53, p. 732 (1920).

"Manufacture and Measurement of Angular Form Gauges," E. A. Swift, *Machinery*, vol. 29, p. 265 (1926).

"Finding Dimensions of Profile Gauges," W. G. Holmes, *Amer. Mach.*, vol. 54, p. 614 (1921).

"Checking Form Gauges," *Machinery*, vol. 28, p. 101 (1926).

"Templet and Position Gauges," H. T. Wright, *Machinery*, vol. 27, p. 65 (1925).

"Simplified Formulae for Calculating Dovetails and Vees," R. Worthy, *Amer. Mach.*, vol. 51, p. 56 E (1919).

"Jigs, Fixtures and Templates," Horner, *Engineering*, vol. 105, pp. 274, 357, 417, 476, 569, 628, 683 (1918).

"Precision Gauges and their Jigs," A. G. Robson, *The Engineer*, vol. 129, p. 575 (1920).

"Measurement of Gauges," E. A. Forward, *The Engineer*, vol. 127, pp. 282, 294 (1919).

"Precision Gauge Manufacture," A. G. Robson, *The Engineer*, vol. 131, p. 313 (1921).

"Some Optical Aids for the Engineer," A. C. Banfield, *Machinery*, vol. 14, pp. 613, 650, 705 (1919).

"Limits for Hole Spacings," *Engineering*, vol. 111, pp. 334, 424, 613 (1921).

"Measuring Taper Gauge," *Machinery*, vol. 33, p. 78 (1928).

CHAPTER VI

NOTES ON THE MANUFACTURE OF JIGS AND POSITION GAUGES

It need hardly be stated that, in the production of repetition work where interchangeability is required, the fullest attention has to be given to the attainment of sufficient accuracy in the jigs and fixtures which are ordinarily used for locating the parts during the various machining operations. Special care has to be devoted to both the design and manufacture of these important accessories, first of all with the object of reducing the machining operations on the parts to the simplest possible processes, thus bringing them within the scope of semi-skilled labour, and, secondly, to ensure that the dimensions of the finished parts shall fall comfortably within the prescribed limits. It is not proposed to enter here into the subject of jig design, but it may be of interest to refer to a few methods and

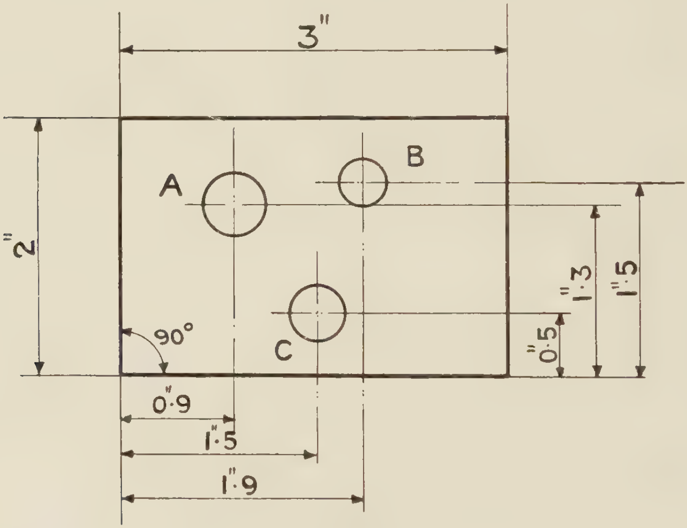


Fig. 128.

appliances used in their manufacture. It is to be understood that the same methods are also applicable to the production of position gauges, but additional care is naturally required to attain the higher accuracy involved. Generally speaking, the accuracy desired in jig work is of the order of 0·001 inch, whilst for position gauges this figure has to be reduced to about a half or sometimes to a tenth.

Practically every jig has one or more bushes to act as guides for drills. These bushes are of hardened steel to withstand usage, and the positions of their centres, either with respect to each other and/or in relation to certain faces or edges, are, of course, important. Let us consider a simple case where a rectangular plate is required with three holes, A, B, C, of certain sizes in the positions indicated in Fig. 128. It will be seen that the holes are located by co-ordinate dimensions off two edges of the plate, but they could equally well have been specified by their centre distances and angular dimensions with respect to one edge from a corner of the plate.

(i) *Button Method.*—This method of locating the positions of the holes for drilling or boring makes use of what are known as "toolmaker's buttons", one of which is shown in section in Fig. 129. They consist of hollow, hardened steel cylinders which can be held down to the work by a central screw as shown. The ends of the cylinders are finished off square, and, for convenience in calculations, the diameters are made accurately to such sizes as 0·3, 0·4, 0·5 or 1 inch.

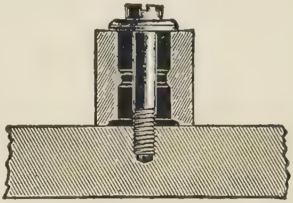


FIG. 129.

For the problem before us we should require three of these buttons of, say, 0·3 inch diameter, and these should be attached to the plate by screws tapped into it at approximately the required positions. The next operation is to locate the axis of each button accurately over the specified centre of its hole. This can be done most conveniently by means of block gauges, using straight-edges placed along the left-hand side and bottom edge of the plate. Each button is set by gently tapping it from one side or another, and, when in position, it is held fast by tightening its screw right home. The plate is then mounted on, say, the face-plate of a lathe, and set so that one of the buttons runs true when tested with a sensitive indicator. This button is then removed, and the corresponding hole bored out to the desired size. This operation of setting up true and boring is then repeated for each of the other buttons in turn, and the work becomes completed.

Experience has shown that, with reasonable care, this method is capable of an accuracy of well within 0·0005 inch in the correct location of holes.

(ii) *Disc Method.*—Another method, which is frequently used in small jig work where a pair of holes, or a group of three, is required at given centre distances, is known as the "disc method". Taking a somewhat similar example to the one just dealt with, suppose we require to bore three holes at positions A, B and C, with centre distances a, b and c, as shown in Fig. 130.* The first step is to calculate the radii of three discs which, when placed in mutual contact, would have their centres separated by the distances specified. These radii are readily found from the three simultaneous equations :

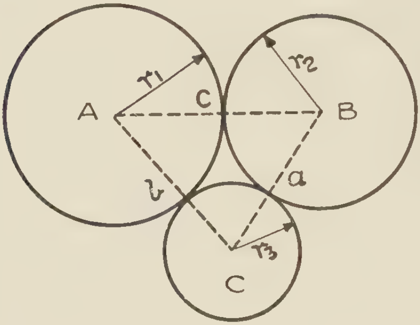


FIG. 130.

$$r_1 + r_2 = c$$
$$r_2 + r_3 = a$$
$$r_3 + r_1 = b$$

Three discs are then carefully ground to these radii and are attached to the jig plate by screws passing through loosely fitting holes as in the case of the tool-maker's buttons, care being taken to see that the discs are pressed into mutual contact before the screws are finally tightened. The plate with the discs attached is then mounted in a lathe, as before, and the holes bored after carefully setting the plate so that each disc in turn runs true. To make it possible to set each disc, their thicknesses may be graded ; operations would be commenced, of course, on the thickest one.

This method can be used to advantage in the production of accurate index plates. Suppose, for example, it is required to space 11 holes accurately round the circumference of a 6-inch circle. An arrangement similar to that shown in Fig. 131 could be used.

---

* If the positions of the holes are given by co-ordinate measurements, as in Fig. 128, it is a simple matter to obtain the centre distances, *e.g.*,

$$AB = \sqrt{(1{\cdot}9 - 0{\cdot}9)^2 + (1{\cdot}5 - 1{\cdot}3)^2}.$$

The plate A, in which the holes are to be made, is provided with 11 equal discs, whose diameters are so chosen that they fit round a 6-inch diameter pitch circle, as shown, inside a rim formed round the periphery of the plate. The diameter of the discs would have to be equal to 6 sin 360°/22, *i.e.* 1·69039 inches, and that of the recess in the plate (6 + 1·69039) inches.

The discs would be fastened to the plate by screws after tapping holes in approximately the desired positions. To enable the discs to be set true, in turn, on the face-plate of the lathe, each of them could be provided with a concentric cylindrical projection, as shown in the sectional view. After setting each disc it would be removed without disturbing the remaining ones, and the hole bored to size.

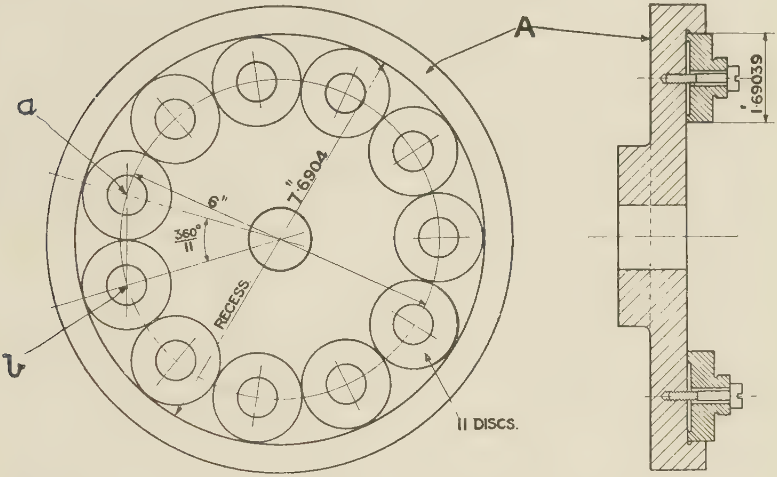


FIG. 131.

To facilitate the setting of the discs, the plate could be mounted with its central hole fitting over a pin set in another plate, mounted on the face-plate of the lathe. Once having set the subsidiary plate so that one disc runs true, the others could be brought into position in their turn by rotation of the index plate round its central pin. An indicator would still be required, but the setting would be confined to only one direction, *i.e.* tangential to the pitch circle.

It need hardly be stated that when carrying out work of this nature on the face-plate of a lathe, particular care should be paid to balancing by suitable counter-weights. In addition, when setting a disc true by means of an indicator, the lathe should be run, as far as possible, at the same speed as that used for the actual boring operation.

If a jig is likely to distort appreciably when revolved at the required speed, it can be bored when bolted down to the table of a milling machine. The boring tool now, of course, has to rotate, and an adjustable type as made by the Pitter Gauge and Precision Tool Company, and shown in Fig. 132, is very convenient for the purpose. The tool proper is held in a block which can be adjusted at right angles to the axis of the spindle, by means of a fine-threaded screw, to suit the diameter of hole required.

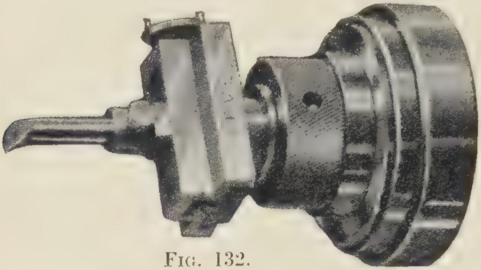


Fig. 132.

In setting a toolmaker's button, or a disc, true before boring on a milling machine, the position of the table is adjusted by the usual feed screws until no variation is shown by an indicator attached to, and revolving with, the spindle.

In the case of drilling jigs and very often also with position gauges, the body is made of cast-iron or tool steel, and to prevent wear, the holes, after being accurately bored as regards position, have hardened steel bushes pressed in. Needless to say, these bushes have to be truly concentric, and for this purpose should be ground externally after mounting on a good mandrel passing through the hole, which has been previously ground, or lapped, to size. It is usually found desirable to grind the outside of the bush slightly tapered so that it can be partly inserted into the hole and then driven gently into position. If the central hole happens to close in very slightly, it can be relapped to size without much danger of disturbing the position of the centre.

Johansson Compound-Slide Table.

A useful tool for spacing out holes in flat jig work has been placed upon the market by Messrs. C. E. Johansson. It consists of a base plate A, Fig. 133, with an intermediate sliding table B and an upper sliding table C. The tables are movable by adjusting screws S, and their motions are arranged to be exactly at right angles and in parallel planes. The upper table, upon which the work is placed, is slotted for the reception of clamping bolts.

In use, the base plate is clamped to the table of a milling machine or face plate of a lathe, and the accurate spacing of holes is accomplished by varying the locations of the two slides by means of block gauges inserted as distance pieces between the contact faces D. For this purpose, the positions of the holes have to be determined in co-ordinate dimensions relative to any convenient pair of axes, such as is illustrated in Fig. 128, p. 106.

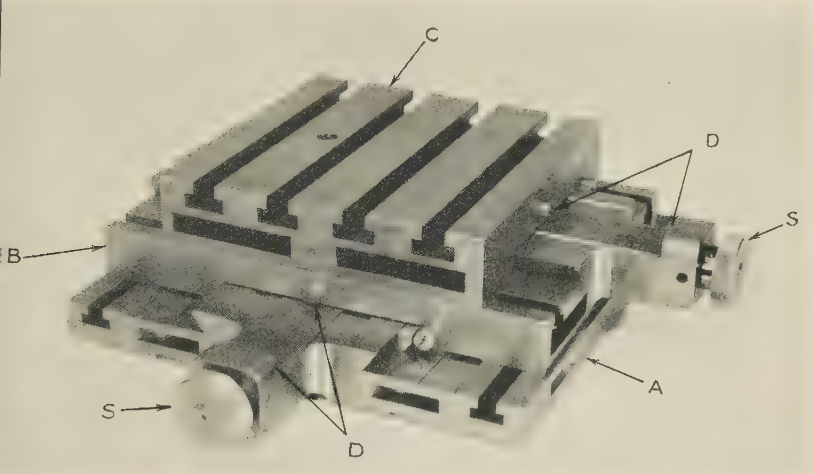


FIG. 133.

These compound tables are made in two sizes, with equal movements in the two directions of 70 mm. and 102 mm. respectively. The corresponding sizes of the upper plates are 190 × 190 mm. and 285 × 290 mm.

Jig-boring and Measuring Machines.

The design of special types of high precision machine tools for marking-off, drilling and boring holes in jigs, position gauges, etc., has received special attention by the well-known Swiss firm, the Société Genevoise. Several sizes of these machines are now made, ranging from one which is particularly adapted for work associated with the watch-making industry up to the largest size, which is capable of accommodating jigs used in the manufacture of petrol engines, electrical machinery, machine tools, etc. It should also be mentioned that, in addition to drilling and boring, these machines can also be used for measuring and verifying jigs after manufacture.

The smallest design of this particular class of machine tool is shown in Fig. 134. It consists essentially of a rectangular-shaped bed carrying a saddle furnished with a turn-table upon which the work is supported. The saddle can be traversed along the bed by means of a micrometer screw, whilst the table itself can be rotated by a worm-wheel through any required angle. The drilling spindle is supported in a bracket bolted to the back of the bed, and is so arranged that its vertical axis passes through the line of traverse of the centre of the turn-table. For measuring purposes, the drilling spindle is replaced by a microscope having a pair of fixed cross-wires in the eyepiece.

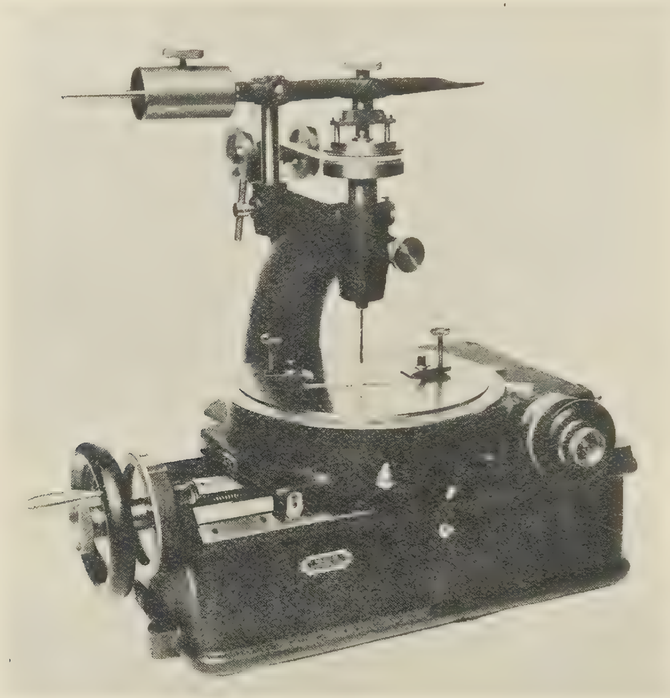


Fig. 134.

From the brief description just given, it will be understood that the operation of the machine is based upon the principle of polar co-ordinates; the distance or radii of the holes from a given centre are obtained from the micrometer traverse, whilst their relative angular locations can be set out by use of the turn-table.

Turning to some of the details of the machine, the micrometer screw has a pitch of 20 threads per inch, and, by means of its divided drum, the position of the saddle can be read to 0·00001 inch over a total travel of 4 inches. The nut attached to the saddle is split so that it can be disengaged from the screw when it is required to move the saddle quickly from one position to another. This feature also does away with unnecessary wear on the micrometer screw. Errors in pitch of the latter are compensated for by the usual form of correcting device, in which the nut is given a small rotation one way or the other by means of a tail-piece, guided by the edge of a suitably-profiled cam-plate set in the bed.

The turn-table is of brass, about 8 inches in diameter, and has 720 teeth cut round its periphery. It is operated by a steel tangent screw provided with a graduated drum, one division of which represents an angular movement of the table of 30 seconds of arc. This screw can be quickly disengaged if it is required to turn the table through any appreciable angle. A scale of half-degrees round the edge of the plate enables it to be set approximately to the required position before the tangent screw adjustment is brought into operation. A small steel spring-centre facilitates the accurate location of a blank on the table before work is commenced upon it. Having located the blank, it is held in position by clips fastened to the plate by screws in the tapped holes provided.

The drilling attachment is capable of producing holes only up to $\frac{1}{8}$ inch in diameter. When larger holes are required, the machine can still be used for accurately marking off their positions by means of a special form of centre-punch held in the bracket. The plate can then be transferred to the face-plate of a lathe, where the holes can be rough drilled and finally bored to size after setting each mark truly central by means of a ball-ended indicator or a microscope. It should be mentioned that, even for the smaller holes, better accuracy is obtained by adopting the latter procedure rather than by drilling the holes in the machine itself, since it is well known that, unless a drill is very carefully ground and guided by means of a bush, it is very difficult to obtain a hole true to any given size or position.

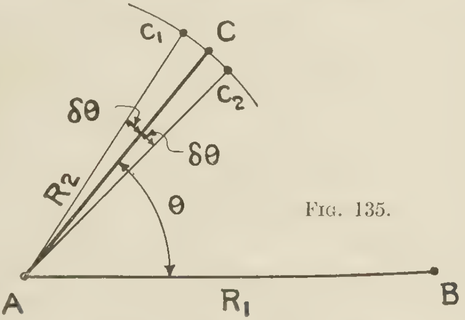


FIG. 135.

Methods such as that employed above for setting out holes by a system of polar co-ordinates are usually limited in their accuracy by the sensitivity of the appliance for measuring or setting out the angles. Consider, for example, a simple case of three holes A, B, C (Fig. 135), where the radii R_1, R_2

from one of the holes, A, and the included angle θ are given. The two holes A and B could be spaced, by means of the micrometer motion of the machine just described, to an accuracy approaching a ten-thousandth of an inch. The same applies to the radial distance R_2 of the third hole C, but the tangential position of C with respect to A will be uncertain to an amount equal to $\pm R_2 . \delta\theta$, where $\delta\theta$ is the uncertainty in setting out the specified angle θ. Assuming that $\delta\theta$ is of the order of 30 seconds of arc, *i.e.* one division on the drum of the worm controlling the turn-table, the distance Cc_1, or Cc_2, would be $0{\cdot}00015\ R_2$. Thus, if R_2 were as much as 2 inches, the tangential variation in the position of C would be likely to amount to rather more than a quarter of a thousandth of an inch.

To maintain an all-round accuracy in the relative location of several holes comparable with that which can be attained in the setting out of their radial distances, it would be necessary, therefore, to resort to specially accurate angle-measuring appliances in the case of jigs where the lay-out of the holes could not be included in a circle of about 4 inches diameter. It is natural, therefore, to find that in the larger sizes of jig-boring machines the principle of rectangular co-ordinates is adopted in preference to polar co-ordinates.

A machine of this type, by the same maker as the one just described, but with an increased capacity of 8 × 8 inches, is shown in Fig. 136. As before, the work-table A can be traversed along the bed by a micrometer screw. The saddle B, which carries the tool holder C, is in this case also capable of micrometer movement along a transverse slide, which is so arranged that the two movements are accurately at right angles. The tool holder itself can be raised or lowered along a vertical slide by means of a rack-and-pinion motion, so as to accommodate work of different heights.

The two micrometer screws of the machine have 10 threads per inch, and the divisions on their drums represent 0·0005 inch, readings being obtainable by means of verniers to a guaranteed accuracy of 0·0001 inch at any position along the 8-inch travel. This high degree of accuracy is attained by the use of compensating devices, of rather unusual form, applied to the micrometer motions. The automatic correction is obtained by altering the angular position of each vernier by means of a lever, the other end of which bears against the edge of a suitably-formed plate which moves with the saddle.

Realizing that this high degree of adjustment will naturally deteriorate, to some extent, as the machine is used, the makers equip each machine with a microscope and a standard scale divided into twentieths of an inch over a length of 8 inches. By clamping the cast-iron box containing the scale to the work table and viewing the scale with the microscope inserted in the tool holder, it is a fairly simple matter to check the accuracy of either of the micrometer motions when desired.* It is of interest to note that the makers guarantee the accuracy of the scale to within 0·0002 inch at any graduation, and supply a table giving its calibration to an accuracy of ±0·00005 inch. The scale is made of 58 per cent nickel steel, which, besides being untarnishable, has the additional advantage of possessing a coefficient of expansion closely equal to that of steel (0·000011 per 1° C.).

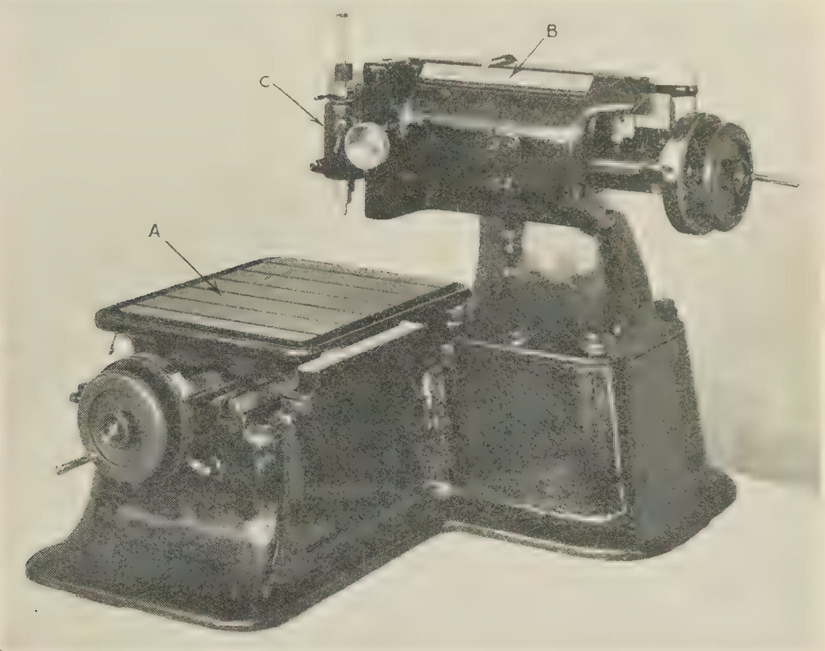


Fig. 136.

As regards tools, the machine is equipped with a centre-punch operated by a small falling weight (this is shown in position in Fig. 136), a drilling spindle and an adjustable boring tool holder. Holes can be drilled up to a diameter of 0·2 inch, whilst the boring attachment can be used for diameters from 0·2 up to 0·4 inch. The spindle is driven through a two-speed gear box by a flexible shaft coupled to a countershaft carrying a three-coned pulley.

---

* Since the scale occupies closely the same position on the machine as the work, the results obtained from such calibrations of the micrometer motions are directly applicable to the actual performance of the machine, in spite of the fact that the slide carrying the tool saddle B is well above the work table. The calibration clearly takes account of any errors in the traverse at the drill point due to any residual lack of straightness of this slide in the vertical plane.

Ordinarily, the work is bolted down to the main table, but where more convenient it can be attached to a 10-inch circular table which is itself fixed to the main table. This circular table is graduated in half-degrees, and can be set to one minute of arc by means of a vernier. As stated above, however, where the highest accuracy is desired on larger work, it is best to make use of both micrometer motions, employing the system of rectangular co-ordinates rather than to use only one screw in conjunction with the circular table. This applies even when the use of the circular table appears to be the more convenient, as when drilling a number of holes on one pitch circle.

According to the maker's guarantee, this machine can be used for measuring purposes on a finished piece of work, or for setting out the centres of a series of holes, to an accuracy of 0·0001 inch. When used for drilling or boring holes, the machine is stated to be capable of an accuracy of 0·0002 inch in their relative location.

The larger sizes of locating and jig-boring machines (of which the Société Genevoise makes four* with co-ordinate motions of 12 × 16, 16 × 24, 24 × 32 and 40 × 51 inches) closely resemble a planing machine, as will be seen from the illustration, Fig. 137. The motions of the work table and the tool saddle are controlled, as before, by automatically-corrected micrometer screws of robust proportions and having five threads per inch, whilst the cross slide carrying the tool is capable of vertical adjustment to suit the height of the work. As regards the diameters and relative positions of holes produced, it is claimed that these machines are capable of an accuracy between 0·0006 and 0·001 inch, according to their capacity.

In addition to special boring tools for dealing with holes up to 4 inches in diameter, these machines are provided with two novel accessories for the initial location of work with respect to the tool. The first is an eyepiece, which can be fitted into the morse taper socket for the tools, as in Fig. 138. This optical device is provided with central cross-wires, and enables a piece of work to be positioned relative to the tool before commencing operations upon it.

The second device, which originated from A. J. C. Brookes at the National Physical Laboratory, is for use in conjunction with a circular table, as in Fig. 139. It consists of a sensitive level fixed in a frame which is held between one centre point on the circular table and another in the tool socket. To arrange the two centres in a vertical line, all that is necessary is to adjust the positions of the main table and the tool saddle by their micrometer screws until no deviation of the bubble occurs as the level frame is revolved between the centres. The axis of the centres will then be truly vertical and consequently square to the work table, which is set up horizontally in the ordinary course of erecting the machine.

---

* See p. 123 for an additional machine with three co-ordinate motions.

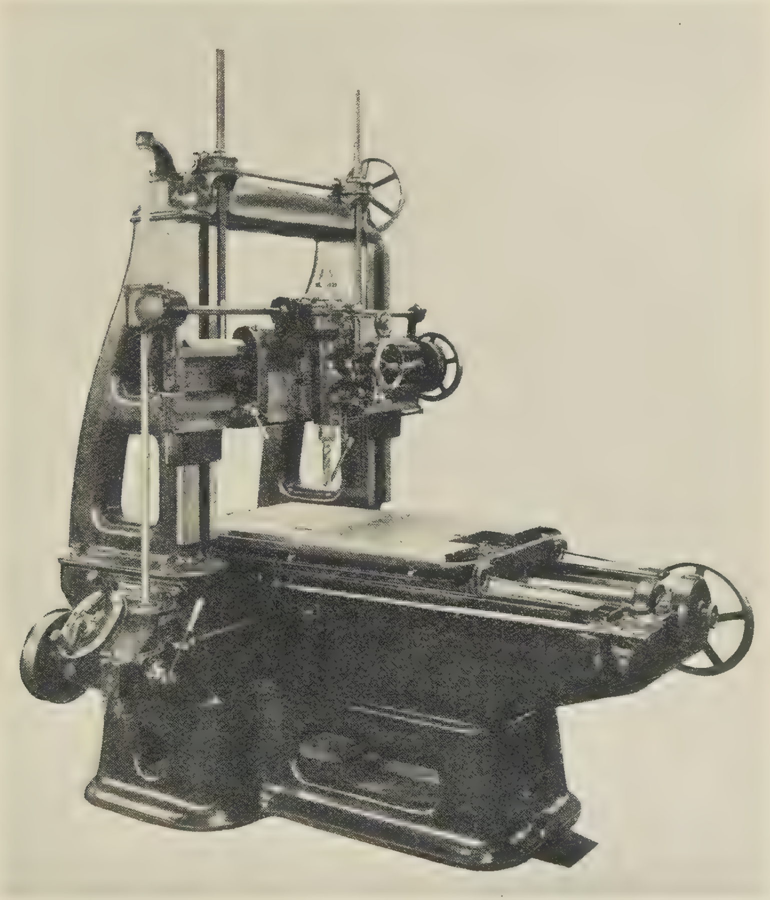


FIG. 137.

The circular table shown in the figure just referred to was specially designed for use with the larger sizes of jig-boring machines illustrated in Fig. 137. Two sizes are made with tables 450 mm. and 600 mm. in diameter respectively. In each case the table is turned by means of a tangent screw provided with a hand-wheel and graduated drum. One revolution of the screw corresponds to a rotation of 1°, and each division on the drum to 10 seconds of arc; a vernier carries the reading to 1 second of arc. The tangent screw and the teeth round the periphery of the table are enclosed in the base casting, and are thus well protected from dirt and accidental damage. An accuracy of from 5 to 8 seconds of arc is claimed by the makers when these tables are used under ordinary practical conditions.

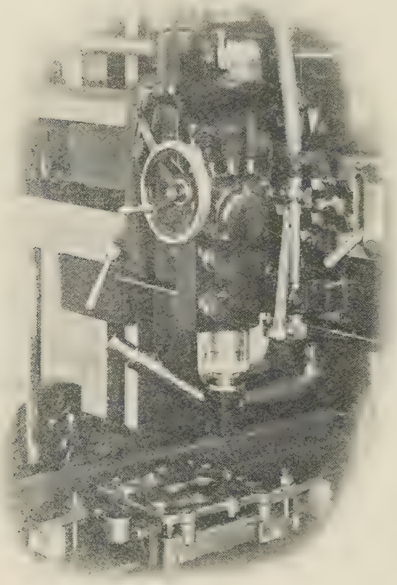


Fig. 138.

The general utility of the S.G. jig-boring machines has recently been increased by the addition of a further type of work table shown in Fig. 140. It will be seen that this table is similar to the circular one just described, in that it can be rotated about its own axis, but it possesses, in addition, a tilting adjustment about a horizontal axis. The latter movement is controlled by a tangent screw, and the settings are read off the graduated scale and vernier to 1 minute of arc.

This form of table, coupled with the facilities given by the coordinate motions on the machine itself, simplifies the setting-out and boring of jigs, including those in which the axes of the holes are not parallel.

The zero setting of the table with respect to the centre line of the drill spindle is obtained with the assistance of the centering level described above. In this case the level fitting is held between the upper centre and a steel ball situated at the point of the centre attached to the table. Knowing the distance from the centre of the ball to the surface of the rotatable table, the axes of rotation can then be located with respect to the micrometer motions on the machine.

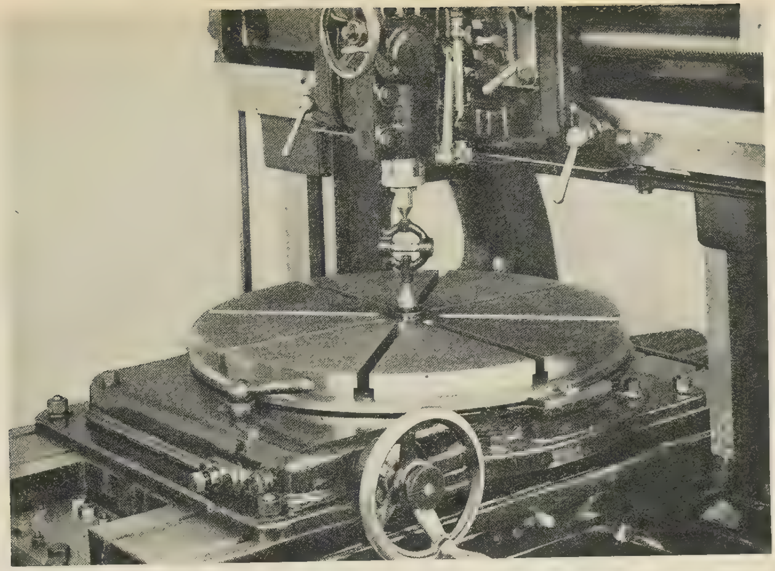


Fig. 139.

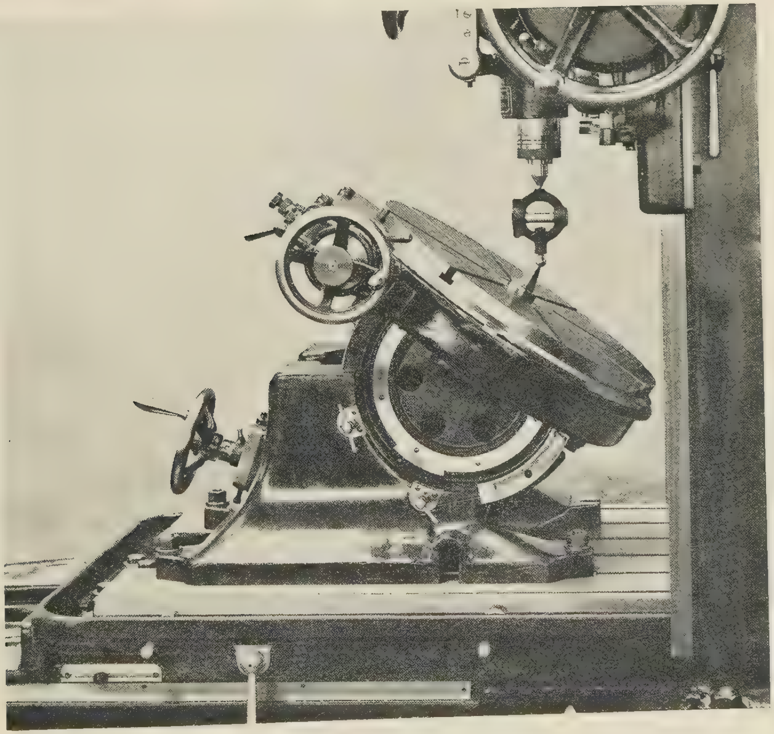


Fig. 140.

The Pratt and Whitney Jig-boring Machine.

A type of jig-boring machine, manufactured by the Pratt and Whitney Co., is shown in Fig. 141. The horizontal work table is supported on a compound-slide, and can be traversed in two directions at right angles through ranges of 18 and 24 inches. The tool spindle is carried in a saddle, the position of which is adjustable vertically through a distance of 12 inches along the face of a robust bracket bolted to the rear part of the bed plate.

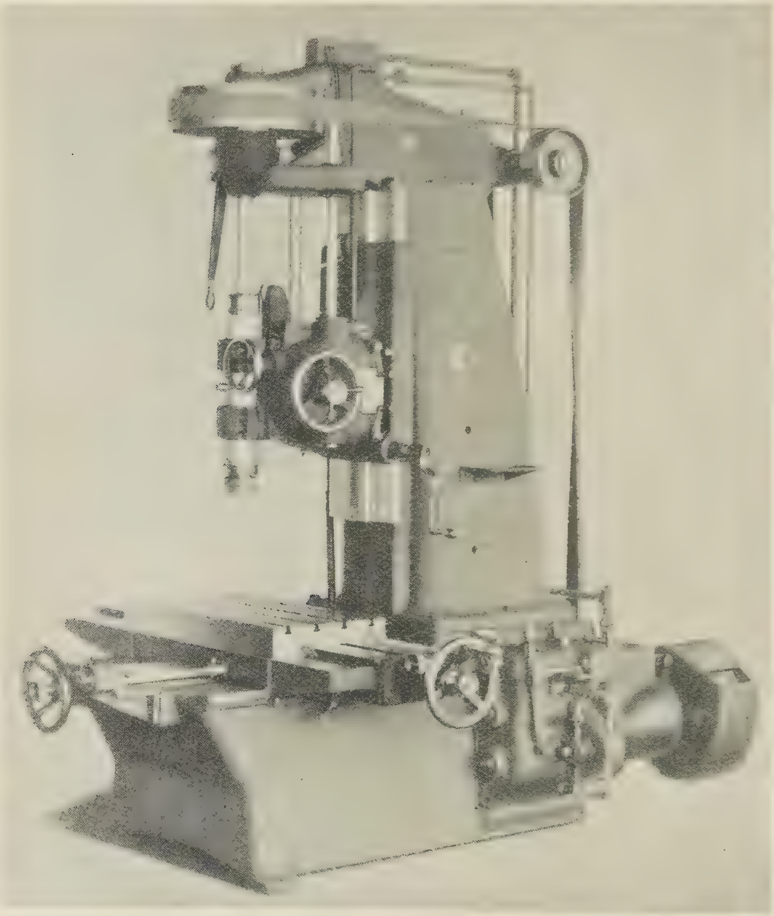


FIG. 141.

The table is moved in the two directions by means of traversing screws operated by the two hand-wheels shown. The setting of its position is, however, controlled by distance pieces, the arrangement in the case of the longitudinal motion being shown in Fig. 142. The distance pieces, which are inserted between an anvil on the table and a dial gauge attached to the bed of the machine, are accommodated in a vee-groove, and consist, in part, of end gauges for giving the whole inches part of the traverse required, whilst fractions of an inch down to 0·001 inch are obtained on an adjustable internal micrometer. The dial gauge serves not only to prevent undue pressure being applied to the distance pieces, but also to give the

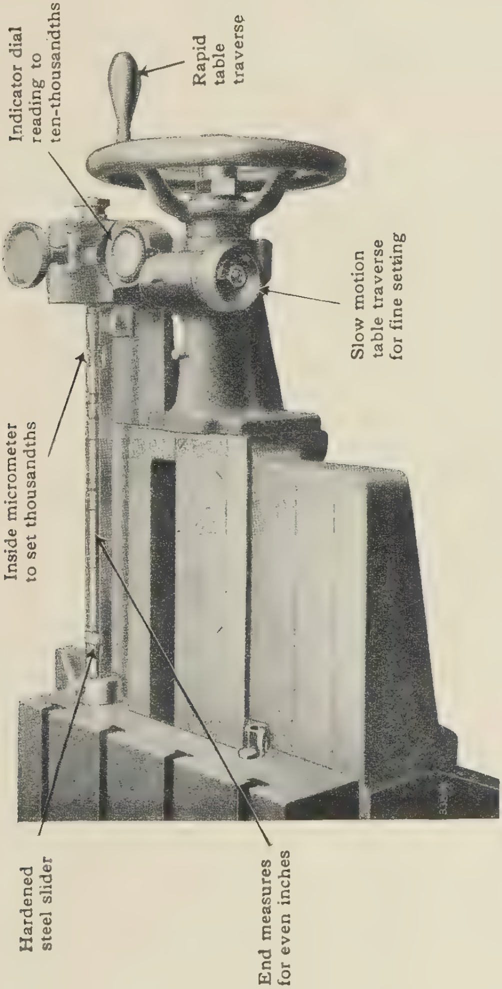

Indicator dial reading to ten-thousandths
Rapid table traverse
Slow motion table traverse for fine setting
Inside micrometer to set thousandths
Hardened steel slider
End measures for even inches

FIG. 142.

ten-thousandths in the traverse. An exactly similar arrangement is provided for the transverse motion. The projection of the anvil faces from the table can be adjusted to allow of the indicators being set to zero when the table is in its initial position.

In setting out circular jigs, it is often more convenient (although usually at some sacrifice of accuracy) to work in polar rather than rectangular co-ordinates, and for this purpose a circular dividing table, Fig. 143, can be used in conjunction with the machine. This table has a face-plate 20 inches in diameter which can be rotated by an accurate worm and worm-wheel motion. For approximate setting, the table can be revolved by the large hand-wheel, its position being noted roughly against the scale of degrees engraved round its periphery. The fine setting is accomplished by turning the small knurled head, which drives the main worm spindle through a second worm and worm-wheel combination. The reading is taken on the large graduated dial attached to the main worm shaft. Settings can be made, by means of a vernier, to 5 seconds of arc. This corresponds to an accuracy of 0·00025 inch on a 10-inch radius.

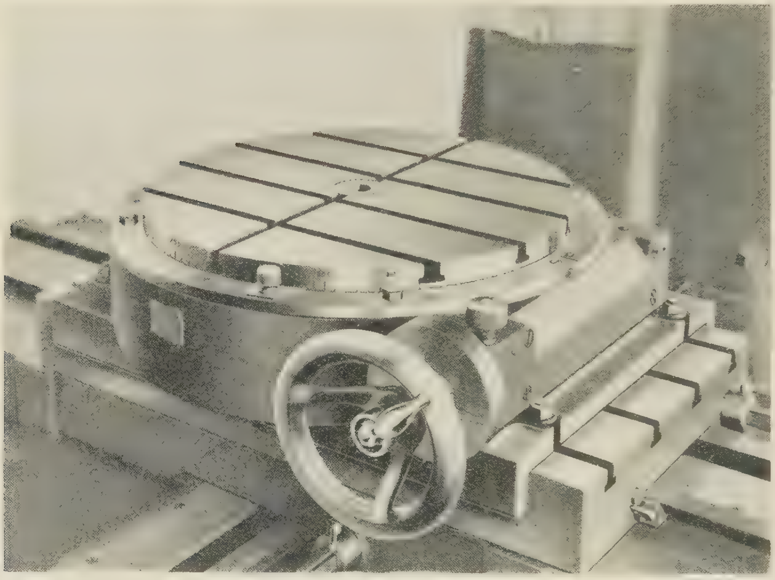


Fig. 143.

Three Co-ordinate Jig-boring Machine.

Quite recently, the Société Genevoise has added to its series of jig-boring machines yet a further type which enables the positioning of holes to be carried out on a system of three co-ordinates, thus facilitating the construction of box-jigs. In addition to the vertical drilling and boring spindle shown in Fig. 137, this machine has two others in a horizontal position, one mounted on each of the vertical side guides. The location of each spindle along its slide is controlled, as in the other machines, by a robust micrometer screw. The table, which has dimensions of 51 × 28 inches, has a travel of 40 inches, whilst the vertical and horizontal spindles can be moved through distances of 28 and 24 inches respectively.

In order to obtain the best results from the machines, the makers recommend that holes should first be drilled about 0·03 inch under size and then opened out to the required diameter with either an adjustable boring-tool or an end-mill made accurately to size. Using proper care with this method, it is claimed that holes bored on this machine will have their centre lines correctly spaced and located to within 0·0008 inch.

ADDITIONAL REFERENCES FOR CHAPTER VI

"High Precision Jig Boring and Locating Machines," Prospectus Nos. 252, 293 and 304, issued by La Société Genevoise.
"Société Genevoise Jig Boring Machine," *Engineering*, vol. 126, p. 350 (1928).
"Pratt and Whitney Jig Borer," *Amer. Mach.*, vol. 68, p. 749 (1928).
"Pratt and Whitney Circular Indexing Table," *Amer. Mach.*, vol. 62, p. 943 (1925).
"Vertical Jig Drilling and Boring Machine" (Pratt and Whitney Machine), *Engineering*, vol. 123, p. 352 (1927).
"Pearson Precision Spacing and Boring Machine," *Amer. Mach.*, vol. 52, p. 631.
"High Precision Jig Boring Machine," *Machinery*, vol. 31, p. 16 (1927).
"Jig-Making Tools," *Machinery*, vol. 30, p. 693 (1927).
"*Accurate Tool Work*," Goodrich and Stanley (McGraw-Hill Co., London, 1912).
"New Adjustable Jig Tools," *Amer. Mach.*, vol. 67, p. 50 E (1927).
"Jig Hole Locating and Boring," *Machinery*, vol. 27, pp. 353 and 421 (1925); vol. 28, p. 776 (1926).
"Precision Gauges and Their Jigs," A. G. Robson, *The Eng.*, vol. 129, p. 575 (1920).
"Generation of Precision Tools," W. E. Hoke, *Machinery*, vol. 25, p. 613 (1925).
"Precision Drilling Machine" (table has co-ordinate motions), C. E. Davies, *Amer. Mach.*, vol. 47, p. 633 (1917).
"Locating Holes to be Drilled at an Angle," A. T. Gregory, *Amer. Mach.*, vol. 62, p. 821 (1925).
"Locating Small Holes accurately in Die Work," *Amer. Mach.*, vol. 48, p. (1918).
"Carson Jig Boring Machine," *Amer. Mach.*, vol. 69, p. 113 E (1928).
"N.P.L. Test on Carson Jig Boring Machine," *Machinery*, vol. 33, p. 186 (1928).
"Locating and Jig-Boring Machine" (Hauser), *Amer. Mach.*, vol. 69, p. 345 E (1928).
"Craley 14″ × 20″ Master Toolmaker for Drilling Jigs," *Amer. Mach.*, vol. 70, p. 189 (1929).

CHAPTER VII

METHODS OF TESTING AND SETTING OUT ANGLES

REFERENCE has already been made to a general method of testing angles by linear measurements made in conjunction with cylinders or spheres.* Various other methods are, however, commonly used in engineering practice. Some of these involve the use of instruments with circular divided scales and/or level tubes, and others the application of special appliances depending mainly upon mechanical measurements of distances. We will consider first a few of the former types of instruments.

INSTRUMENTS WITH CIRCULAR SCALES OR LEVEL TUBES

(i) **Bevel Protractors.**

Probably the most familiar angle-measuring tool is the Brown and Sharpe bevel protractor, Fig. 144. This has a base plate engraved

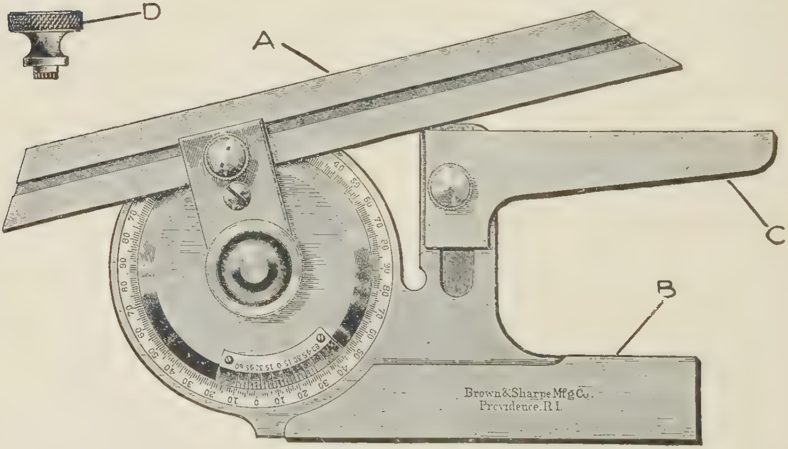


FIG. 144.

* See Chapter V.

with a scale in degrees, about the centre of which can be rotated a circular plate to which is clamped a straight-edge A. The angle between the latter and the slotted edge of a projecting portion B of the base plate is indicated on the scale by a vernier reading to 5 minutes of arc. The angle between the two edges referred to is capable of fine adjustment by rotation of a knurled-headed pinion D, which, on being inserted in a hole at the rear of the base plate, engages with teeth cut round the periphery of the circular plate. Having made the setting, the plate can be locked in position by the central binding screw shown. For some purposes it is convenient to use the auxiliary base C, the upper edge of which is set parallel to the main base.

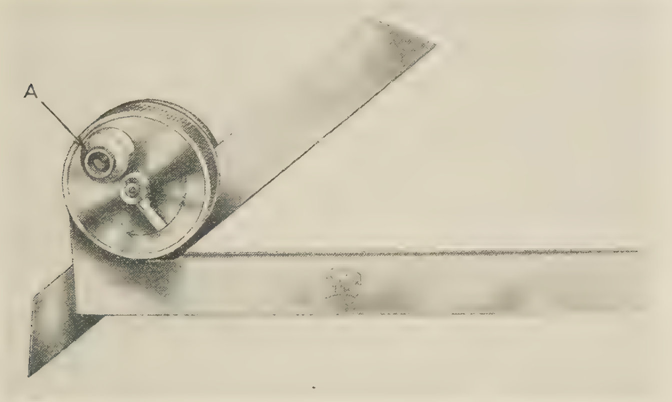


FIG. 145.

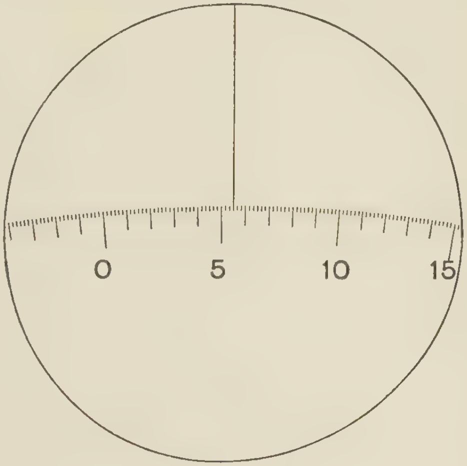


FIG. 146.

A somewhat similar form of instrument, made by Messrs. Zeiss, is illustrated in Fig. 145. In this case, however, the circular scale is engraved on glass, and the angle between the movable straight-edge and the base is read by viewing the scale through a small magnifying lens A with the instrument held up to the light. The appearance in the eyepiece is shown in Fig. 146, from which it will be seen that the divisions of the scale represent 10 minutes of arc. The fineness of the graduations readily permits of estimation to a half or a quarter of a division.

(ii) **Dividing Head** (Zeiss).

The universal type of dividing head is a machine-tool accessory met with in practically all tool rooms. As is well known, the degree of accuracy obtained by the use of this appliance depends largely upon the perfection of gearing and division plates incorporated in the tool. In the Zeiss optical dividing head the makers have produced a tool which eliminates such factors, its accuracy being derived from a circular divided scale mounted directly on the spindle carrying the work. It will be seen from Fig. 147 that this change in internal design has been effected without sacrificing any of the general robustness of the usual type of dividing head. By the new arrangement, all question of backlash between gearing is eliminated, together with the usual difficulty in spacing out awkward angles. The required angles are read off directly on the scale to within an accuracy of 15 seconds of arc.

The general arrangement of the optical head is given in Fig. 148. The spindle is rotated by the worm and worm-wheel shown, the angular setting being read on the circular scale A by means of the microscope B. An arrangement consisting of a reflecting prism and mirror is fitted for illuminating the scale by light entering the opening C. The worm spindle is mounted in eccentric bearings, and can be readily disengaged, if necessary, by rotating the arm D. When set in position, the work spindle can be held rigidly by a specially designed clamp E. Provision is made, as usual, for tilting the axis of the spindle, the angle being read off the scale shown in the front of Fig. 147.

The circular scale A is graduated on glass into degrees. Subdivisions are obtained by means of a scale in the eyepiece having 60 divisions, each representing 1 minute of arc. The clearness of both these divisions and those on the glass ring enables the angle to be estimated to the nearest quarter of a minute. The appearance in the eyepiece is shown full size in Fig. 149. The reading in this particular setting is $45° 23\frac{1}{2}'$.

When used for light finishing cuts or during inspection, the makers claim that by the use of this optical head a general accuracy

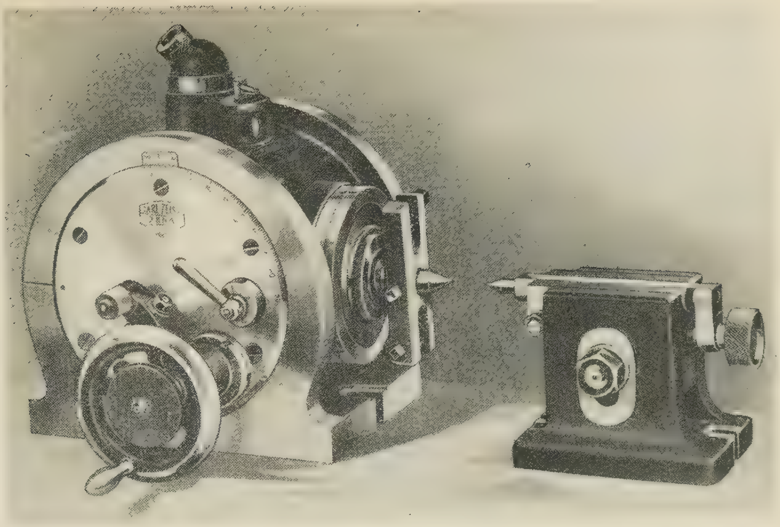


FIG. 147.

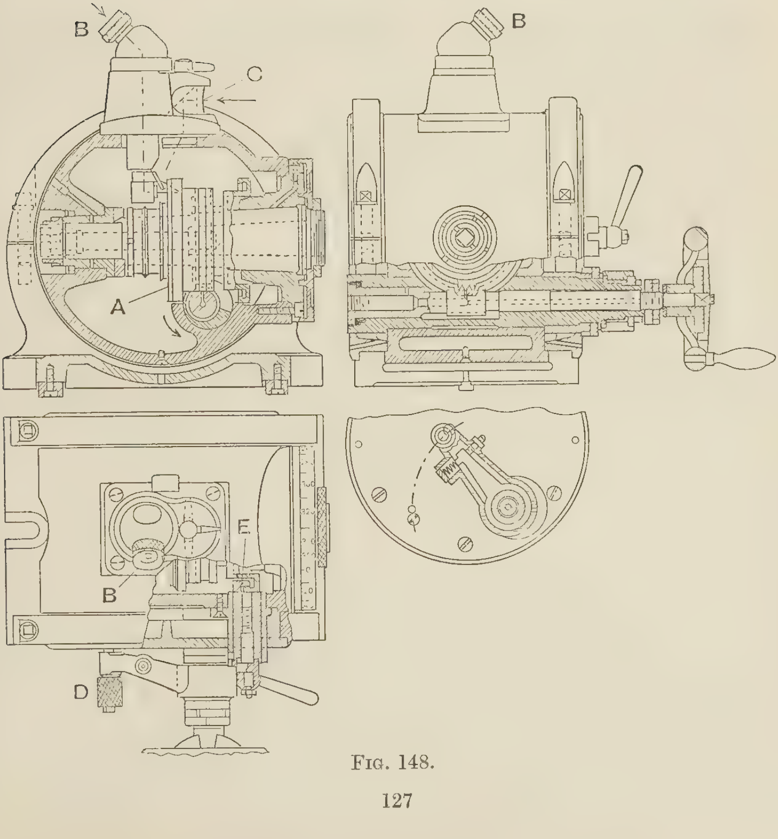


FIG. 148.

of ±20 seconds of arc can be attained. Any tendency there may be for the spindle to spring under heavy cuts can readily be observed in the microscope, and even under these conditions the accuracy of finished work is stated to be within ±80 seconds of arc.

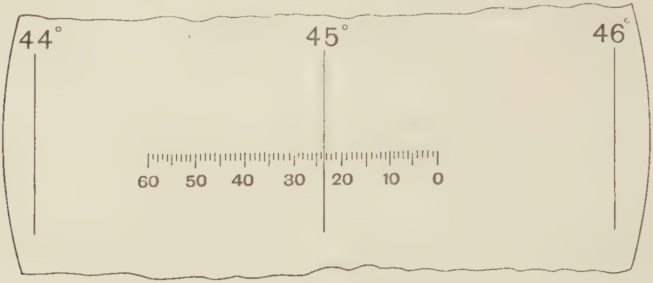


Fig. 149.

(iii) **Circular Division Plate.**

Modelled on the lines of the table of a circular dividing machine, the plate shown in Fig. 150, which is a production of the Société Genevoise, serves useful purposes in jig and position gauge work or in the graduation of circular plates. It is so constructed that it can be bolted to the table of a drilling or milling machine, or can be used under the scribing head of a linear dividing machine.

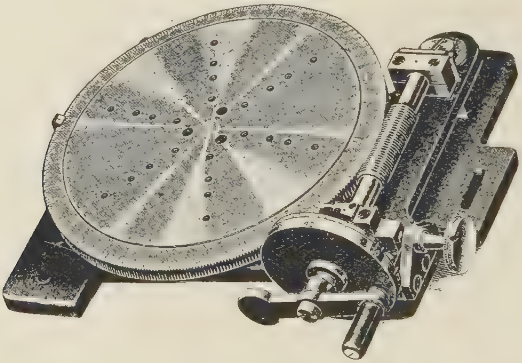


Fig. 150.*

The principle of operation has been described on page 112, where reference will be found to a similar fitting incorporated by the same maker in the design of jig-boring machines.

---

* The plate illustrated is of early design, but shows clearly the principle incorporated in the more recent plates, one of which will be seen in Fig. 139, p. 119.

(iv) Circular Dividing Machine.

The Swiss firm referred to above has paid particular attention to the design and manufacture of circular dividing machines of various sizes capable of accommodating work from about 9 inches up to as large as 24 feet in diameter. The accuracy of the finished work ranges from 1 to 15 seconds of arc, according to the type of machine used. A typical example of these machines is given in Fig. 151.

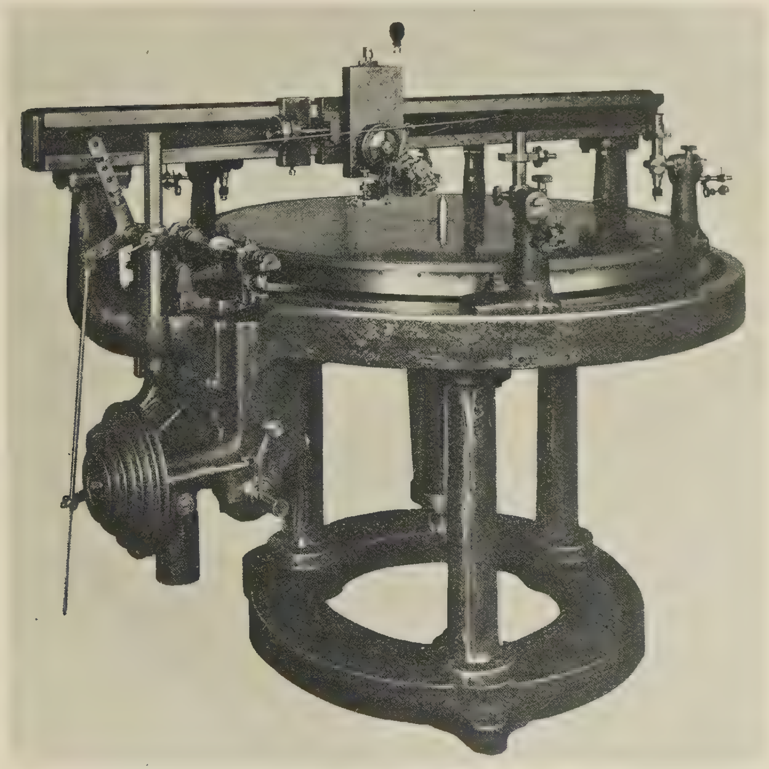


Fig. 151.

The circular table upon which the work is centred is carried in a long, tapered bearing provided with an adjustable abutment at the foot. Round the periphery of the table there are 720 accurately spaced teeth, which engage with a tangent screw to be seen at the left of the figure. This screw has a ratchet wheel at one end, and, by means of adjustable stops, it can be turned repeatedly by automatic means through any desired interval corresponding to the spacing of the graduations to be ruled. In addition to the ratchet wheel, there is also a divided drum and vernier; one division of the latter corresponds to an angular motion of the table of 1 second of arc.

Residual errors in the spacing of the teeth round the table are counteracted by a compensating device, which operates as follows. The axial position of the tangent screw in its bearings is controlled by an adjustable screw abutment at one end. This screw carries, at right angles, an arm terminating in a roller which presses against the edge of a circular rim projecting round the lower surface of the table, as seen in the illustration. This rim is profiled in accordance with the results of an initial calibration of the table. As the table revolves, the roller follows the profile of the rim and gives a varying angular motion to the lever, which results in corresponding endwise displacements of the tangent screw. These movements are imparted to the table either as positive or negative corrections to the motion derived from the rotation of the tangent screw. It is by means of this refinement that such a high accuracy as one second of arc is attained in the displacements of the table.

In addition to the driving teeth round its edge, the table is also provided with a circular scale engraved in half-degrees on a silver strip near the circumference of its upper surface. This scale can be viewed by micrometer microscopes held in vertical brackets, the positions of which can be varied round the circular slot in the bed plate. These microscopes give a magnification of from 30 to 40 times, and one division on their micrometer drums corresponds to an angle of one second.

The beam which is seen supported over the top of the table carries the scribing mechanism, the position of which is adjustable both along the beam and vertically, so as to suit work of different diameters and thicknesses. In certain types of these machines, the scribing mechanism can be replaced by a small, independently-driven milling head for cutting toothed wheels where the highest accuracy is desired.

It is to be understood that, in dividing a disc, the whole action of the machine can be made automatic once the work has been set up and the necessary adjustments made. In automatic working, the continuous motion of the pulley shaft of the machine operates the feeding mechanism and the scribing gear alternately. After the table has been advanced through the required angle by means of the ratchet wheel on the tangent screw, the scribing mechanism comes into action and rules a line. This is followed by another equal displacement of the table, which is controlled by the stops on the tangent screw spindle. A second line is then ruled, and so on. At the completion of a revolution the machine stops automatically.

The lines ruled are not necessarily all of one length. There is provision in the scribing head for producing the usual arrangements of long and short lines, which are repeated automatically right round the scale.

(v) Apparatus for Testing Circular Graduations.

The necessity sometimes arises for checking the accuracy of graduated discs, drums of measuring instruments, or trial rulings made on a circular dividing machine as a test on its performance. Two methods are possible. The first is to mount the disc on the same arbor as a standard circle of known calibration, and to compare corresponding intervals on the two scales. The alternative method requires no standard of reference; various intervals on the scale are intercompared throughout the complete circle, and, from the difference found, it is possible to state the errors in the graduations tested.

Tests such as those mentioned can be readily carried out by either of the methods on an instrument designed by the Société Genevoise, a photograph of which is shown in Fig. 152. This instrument will accommodate circles from 6 inches up to 24 inches in diameter. The circle to be tested is mounted on a horizontal table attached to the upper end of a vertical spindle, adjustments being provided for accurately centering the disc true with the axis of the spindle. The lower end of the spindle has a toothed plate, which can be rotated by a tangent screw in the same manner as in a circular dividing machine. When not required, this tangent screw can be taken out of engagement. The graduations on the divided circle are viewed with micrometer microscopes, arranged in two pairs, each situated across a diameter. From the illustration, it will be seen that each pair of microscopes is supported on a slide, along which they can be adjusted to suit the diameter of the circle under test. One of the slides is solid with the base of the instrument, whilst the other can be rotated about the main axis so as to vary, at will, the angular setting between the two pairs of microscopes. In addition to an adjustment for height, each microscope is provided with a focussing screw; they can also be set at any angle between the vertical and horizontal positions to suit the angle of the periphery of the graduated circle being tested. The microscopes can be used at a magnification of either thirty or sixty times, according to the quality of the graduations, by simply changing objectives.

When testing a disc by comparison with a standard circle, the two are mounted one above the other, with a microscope reading on each. A direct comparison of the scales is then possible. To carry out the other method of test, the two pairs of microscopes are set at an angle of, say, 30° (approx.), and readings are taken on the 0 and 30° graduations, using two adjacent microscopes. The disc is then rotated through 30° (approx.) by means of the tangent screw below, and a second pair of readings is taken on the 30° and 60° marks. This is repeated round the circle, after successive rotations of 30°, until the 330° and 360° divisions are reached.* The micrometer readings thus obtained enable the errors to be determined at the graduations 30°, 60°, 90°, etc. By going through the whole operation twice more, beginning on the 10° and 40° marks, and then at 20° and 50°, concluding with another set

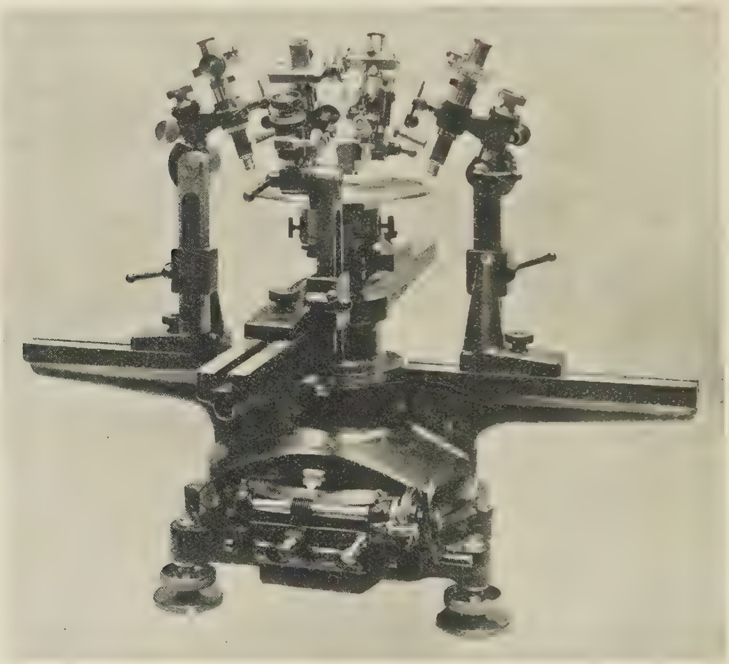


FIG. 152.

---

* The tangent screw has a rachet wheel and pawl which, together with an arrangement of stops, permits of the spindle being turned rapidly through equal increments of angle.

of observations with the microscopes set at 40° (approx.) apart, it is possible to determine the errors at every 10° round the scale. The method of calculation is outlined in Appendix IV. Further subdivision can be made by setting the microscopes at appropriate angles and taking readings round the complete circle.

This method of testing circular graduations by microscope readings on the lines is capable of extremely high accuracy, which, it should be noted, improves more and more as the diameter of the circle increases. For example, suppose that it is possible to observe the position of a line under the microscope to only $\pm 0{\cdot}00005$ inch; on a radius of 3 inches, this represents an angle of between 3 and 4 seconds of arc.* Seeing that with good graduations observations are possible to something of the order of $\pm 0{\cdot}00001$ inch, the uncertainty in determining the errors of a 6-inch circle should not exceed ±1 second.

With modern dividing engines it is possible to graduate circles correctly to a second of arc. In attempting to utilize a circle to such accuracy, the difficulty usually met with is to mount it so that the centre about which the angles are to be measured coincides with that about which the graduations were cut. Eccentricity gives rise to periodic errors in the angular measurements. For example, an eccentricity of 0·0001 inch in the mounting of a 6-inch circle would produce errors amounting, in the maximum, to ±6 seconds. It is only by taking duplicate readings at opposite extremities of a diameter that errors due to this cause can be eliminated in accurate measurements of angles.

(vi) Gauge Clinometer.

A type of instrument designed at the National Physical Laboratory on the principle of the clinometer, is shown in Fig. 153. It resembles the bevel protractor in having two plates, but the upper one A, instead of being provided with a straight-edge, has a sensitive spirit-level tube B attached to it. In measuring the angle between two edges of a plate such as C, the latter is held rigidly in a vice, and the straight-edge D on the base plate is placed on one of the edges. The second plate is then revolved on the centre pin until the bubble of the level tube is in the middle of its run, the fine adjustment being made by the tangent screw E. The reading of the angular scale is then noted on the vernier F, and the straight-edge is transferred to the second edge of the plate. The level is again adjusted, and a second reading is taken. The difference between the readings gives the angle between the two edges. The angular scale G is divided on a silver strip, and readings can be made to one minute of arc. This instrument proves very useful when setting up jig-work on a milling machine or surface grinder.

---

* 1 second of arc $= 4{\cdot}8 \times 10^{-6}$ radians.

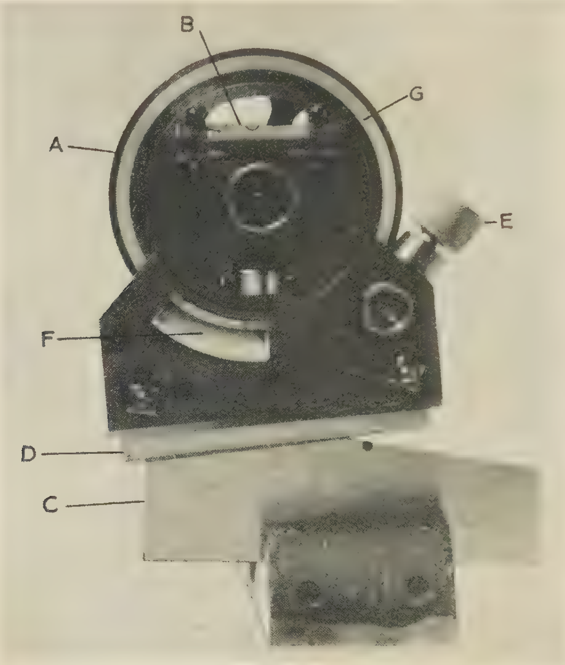


Fig. 153.

(vii) **Precision Clinometer** (La Société Genevoise).

Another instrument, which is particularly useful in the machining of jigs and angle work in general, is shown in Fig. 154. It is

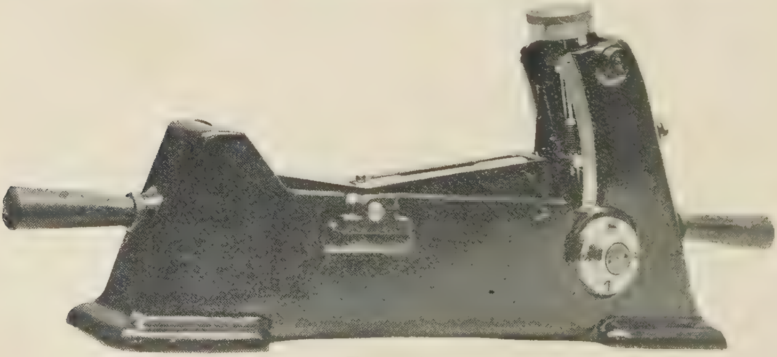


Fig. 154.

somewhat similar in principle to the one just described. The body consists of a substantial iron casting of U-shaped section, having a finished base. In the recess of the casting is housed a frame ~~A~~ (Fig. 155), capable of tilting in a vertical plane about journal bearings at B, and carrying a sensitive level tube C. One division on the latter corresponds to a change in angle of 6 seconds of arc. The angular position of the frame with respect to the base is controlled by a worm spindle ~~D~~, which engages with teeth cut in the face of a sector forming part of the frame. The worm spindle itself is carried in a bow-shaped casting pivoted at the bottom at E, contact between the teeth being maintained by the pressure of a spring F.

The worm spindle has a graduated drum bearing 180 divisions, each of which corresponds to an angular movement of the frame A of 10 seconds of arc. Each complete turn of the spindle, therefore, gives a displacement of half a degree, and a scale marked in this unit, up to the available range of 30°, is to be seen ~~in Fig. 154.~~ When placed upon a truly horizontal surface, the bubble of the level is central when the reading is set to zero. In order to incline the base at any specified angle within

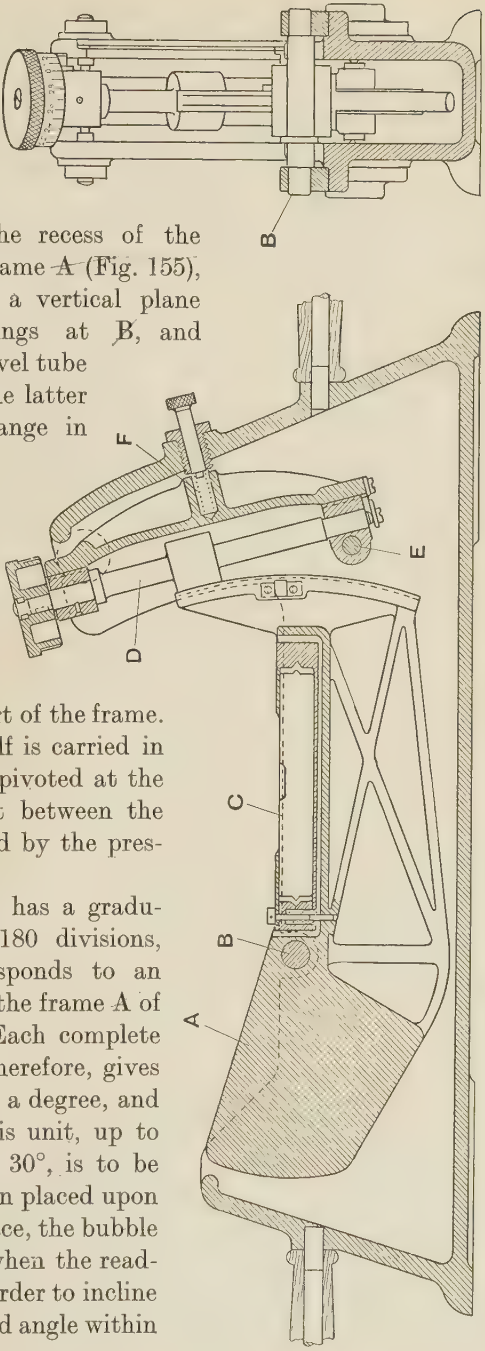


Fig. 155.

the range of 30°, the reading is first set to the desired angle, and the whole instrument is then tilted until the bubble once more becomes central.

The makers claim an accuracy of 10 seconds of arc for angular measurements within the range of the instrument.

(viii) **Adjustable Level** (Cooke, Troughton and Simms Ltd.).

The level shown in Fig. 156 is intended primarily for use in levelling operations on shafts, machined surfaces, etc. The cast-iron base, which is $2\frac{1}{2}$ inches wide and 8 inches long, has a flat bottom and also a 120° vee for use on shafts.

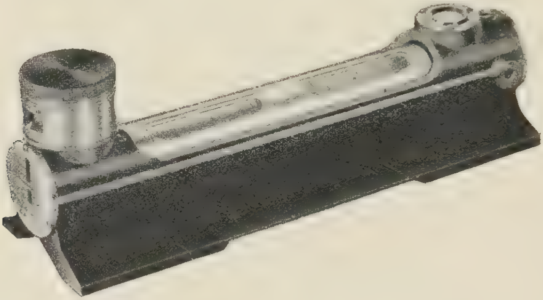


FIG. 156.

Should the surface under test not be truly level, its inclination can be accurately measured, provided it falls within a range of about 2°. For this purpose, the tube carrying the level can be tilted with respect to the base by means of a micrometer screw at one end. The drum of the latter is conveniently graduated so as to give the inclination either in degrees and minutes or in thousandths of an inch per foot run. The sensitivity of the level vial is such that a gradient of 0·001 inch in 12 inches results in a 0·1-inch movement of the bubble. This corresponds to a radius of curvature of 100 feet.

(ix) **Level Tubes.**

Up to within fairly recent years level tubes were produced by a process of hand-grinding. This has now been superseded by mechanical methods of internal grinding, which not only give greatly improved uniformity in the radius of curvature along the tube, but also render the tube circular in cross-section, so that theoretically the sensitivity remains the same, even if the tube be turned on its axis.

Variations in the length of bubble which ordinarily accompany temperature changes are undesirable in level tubes used for accurate purposes. In the first place, owing to the almost unavoidable presence of slight irregularities in the bore of the tube, the two ends of the bubble may not expand or contract equally, with the result that the zero position becomes displaced and the adjustment of the instrument is disturbed. Moreover, since the controlling forces on the bubble are dependent upon the length of arc which it occupies in the tube, shortening of the bubble tends to increase its stickiness and impart to it a reluctance to answer to small angular movements of the tube.

The trouble is overcome to some extent by the use of "chambered" levels. These tubes have an air reservoir at one end, separated from the rest of the tube by a glass disc having a hole at the bottom (see Fig. 158, p. 138). By holding the tube vertically, with the chamber at the bottom, air escapes from the latter into the main part of the tube, thus increasing the size of the bubble ; to diminish the bubble, the tube is held in the inverted position. With such tubes it is possible to restore the bubble to a given length (usually the distance separating the central lines of the two scales on each side of the centre of the tube) at any temperature. This method of adjustment becomes almost impracticable when the level tube is fitted to a large instrument, and has been superseded by a type of tube introduced in 1924 by Messrs. E. R. Watts. This maintains a constant length of bubble over quite a wide range of temperature variation. To understand the principle underlying these tubes, it should be realized that a rise in temperature tends, on the one hand, to shorten the length of the bubble on account of expansion of the spirit, and, on the other hand, to lengthen it by reducing the surface tension of the liquid. With the ordinary circular section tubes, the former effect predominates, but by giving the tubes a suitable elliptical section, Messrs. Watts have been able to balance the two opposing effects with the result mentioned above.

(x) Apparatus for Testing Level Tubes.

In testing surveying instruments fitted with level tubes it is often necessary to ascertain the sensitivity of the tubes and the uniformity of their calibration. Instead of removing the tubes from the instrument and thereby disturbing their adjustments, the whole instrument can be placed upon a tilting table such as is shown in Fig. 157. The platform upon which the instrument rests is carried on a framework, which can be tilted about a pair of ball-ended feet at one end by means of a micrometer head situated at the other extremity. If the length of the tilting base is of the order of 36 inches, the apparatus will deal comfortably with level tubes having a sensitivity as fine as 5 seconds of arc per 0·1-inch run of the bubble. This will cover the requirements of most surveying instruments. To obtain satisfactory results it is, of course, essential that the testing apparatus should rest on a good solid foundation.

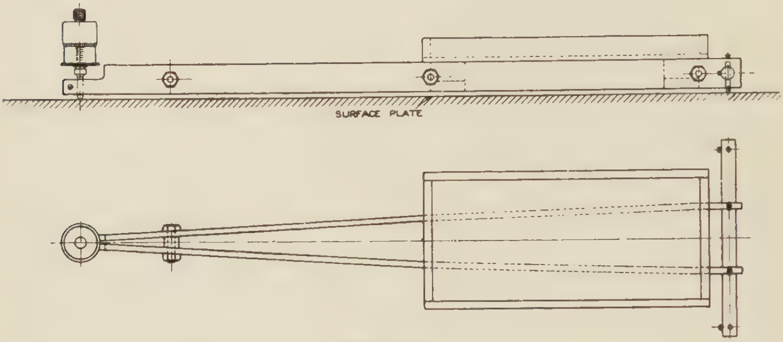


Fig. 157.

The same apparatus can be used for testing unmounted level tubes, but a rather more convenient appliance for this purpose is shown in Fig. 158. The tube to be tested is supported in vees on a tilting lever A, which is hinged to a base plate B by means of a flexible steel strip C. The inclination of the lever can be varied by inserting a series of block gauges in turn between contacts at its free end. The ball D which forms the upper contact is 12 inches from the steel strip, whilst the lower contact E comprises three balls pressed into a hole in the base plate. The cam F is used for raising the lever when changing the gauges.

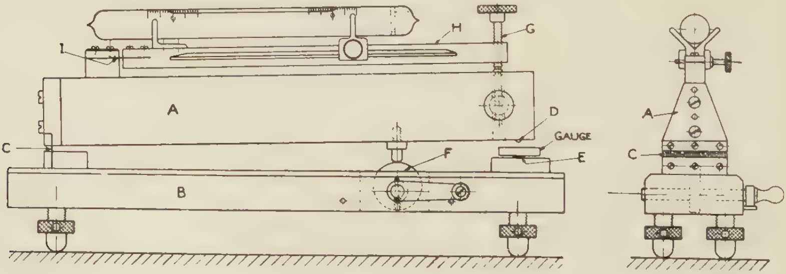


Fig. 158.

The base plate has levelling screws as shown, but a more sensitive adjustment of the zero position of the level tube is obtained by means of the differential screw G. This allows the subsidiary lever H, on which the tube is supported, to be tilted with respect to the main lever by bending the steel supporting strip I at the left-hand end. The differential screw has one portion threaded $\frac{1}{4}$ inch B.S.F. (26 T.P.I.) and the other No. 0 B.A. (25·4 T.P.I.), so that the sensitive adjustment required, in the case of large radius levels in particular, is therefore readily obtained.

The series of gauges used for testing any particular level tube naturally depends upon its sensitivity. In this connection it is convenient to remember that for a tube of 100 feet radius, a tilt of 0·001 inch on the 12-inch lever would cause a deflection of the bubble of exactly 0·1 inch. Generally, it will be found that block gauges from the thousandth of an inch or hundredth of a millimetre series will serve for most level tubes. For the more sensitive tubes it becomes necessary to resort to a series of gauges differing consecutively by only 0·0001 inch.

This apparatus has been used at the National Physical Laboratory and found to function quite satisfactorily for level tubes with sensitivities as fine as one or two seconds of arc per 0·1-inch movement of the bubble.

It is of interest to note that, owing to flexure, the radius of curvature of the more sensitive tubes varies to some extent according to the position of the supporting vees. For this reason, it is usual to arrange the vees at the "Airy" points, and the same positions of supports should be adhered to when subsequently mounting the tube in any apparatus.

Angle Measurements by Indirect Methods

Some attention will now be given to other methods of setting-out or measuring angles in which circular scales and level tubes are not used.

(i) **Johansson Angle-pieces.**

Some few years ago Messrs. Johansson introduced a type of angle template, a set of which is illustrated in Fig. 159. These templates consist of hardened steel plates about $2 \times \frac{3}{4} \times \frac{1}{16}$ inches thick with their edges ground and lapped. From the illustration it will be seen that the plates are generally of three shapes, examples of which are shown in Fig. 160. The long sides of each plate are

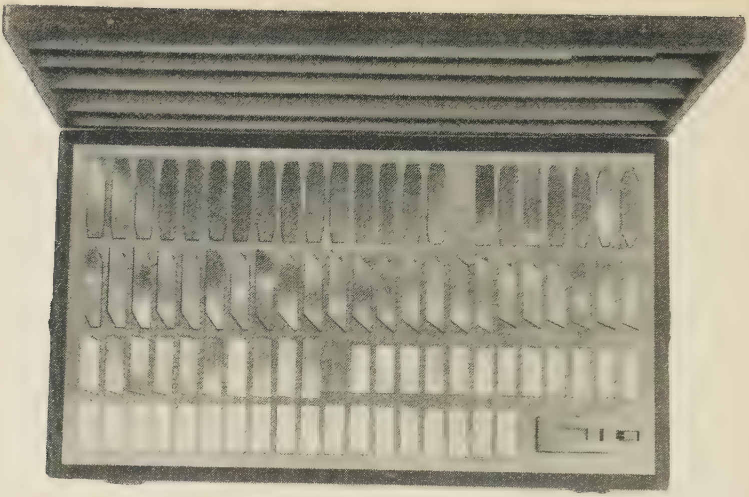


FIG. 159.

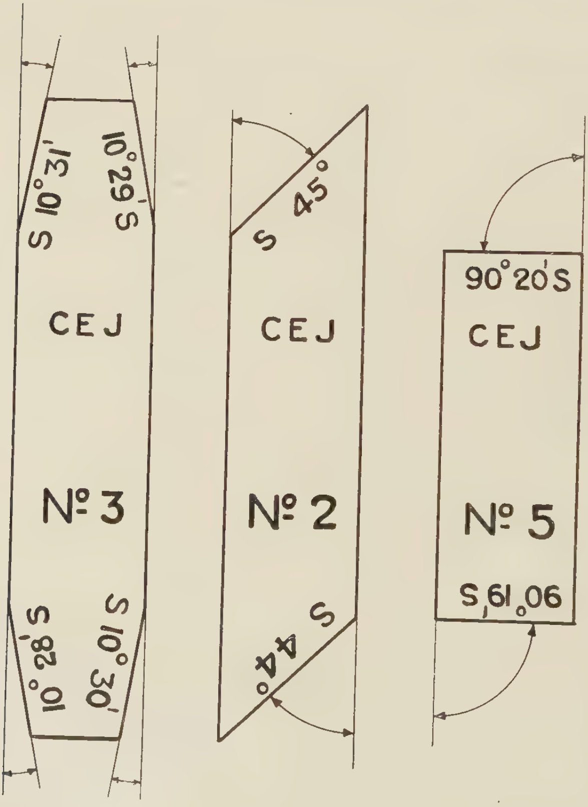
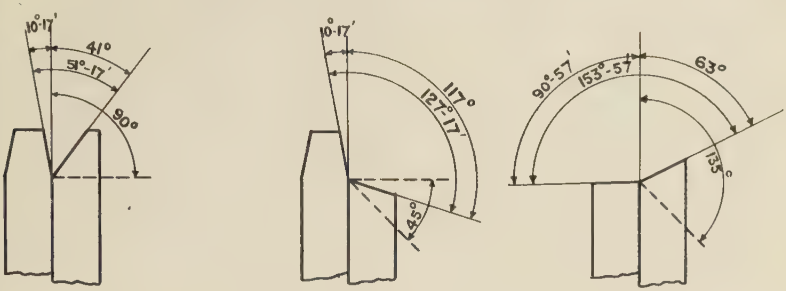


FIG. 160.

accurately parallel, and the angles marked upon the plates represent the inclination of the shorter bevelled edges with the prolongation of the adjacent long edge.

In the full set of 85 pieces, the first series of 15 covers the range 10° to 11° in intervals of a minute, each plate having four angles upon it. The second series embraces angles from 0 to 90° in steps of a degree, whilst the third series of 30 pieces is in intervals of a minute from 90° to 91°.



10° - 101°
FOR EACH MINUTE.

100° - 146°
FOR EACH MINUTE.

89° - 226°
FOR EACH MINUTE.

Fig. 161.

The pieces can be used either singly or, more generally, in pairs, as in the three diagrams of Fig. 161. With the exception of angles between 0 and 10°, 350° and 360°, it is possible by this means to build up any angle to one minute. When used in combination, the plates are held in a clamp, Fig. 162. This figure illustrates the checking of the angle of a 55° thread tool gauge.

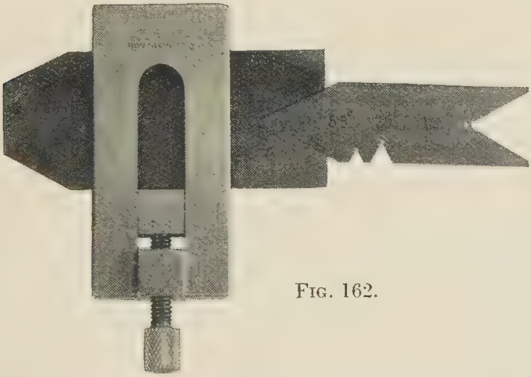


Fig. 162.

Although this system of angle templates is no doubt very convenient as a means of building up a large number of angles from comparatively few pieces, their application to ordinary engineering practice, judging from the author's experience, appears to be rather limited. Their usefulness in no way approaches that of the block gauge system, the origin of which, as is well known, falls to the credit of the same makers.

Methods of testing these angle gauges have been devised at the National Physical Laboratory, making use of either an accurate spectrometer,* the angle-measuring device of Tomlinson's gear measuring machine,† or a sine bar and sensitive level.

(ii) The Use of Cylinders and Block Gauges for Setting Out Angles.

When machining jigs, fixtures and position gauges, it is often necessary to incline the work at certain angles in order to grind some of the faces or bore holes with inclined axes. To do this it is sometimes convenient to have angle templates with which to set out the desired angle of inclination of the work.

Suppose, for example, that an angle template of $\frac{1}{8}$-inch plate is required for 10°, with an overall length of about 6 inches. A method of producing such a template is shown in Fig. 163. Having ground one edge of the plate, it can be mounted on a suitable angle plate with its finished edge resting across two discs, D_1, D_2, separated by a block gauge G. Convenient discs for the purpose would be 1 inch and $1\frac{3}{4}$ inch diameter. The length of the gauge G is obtained from the relation,

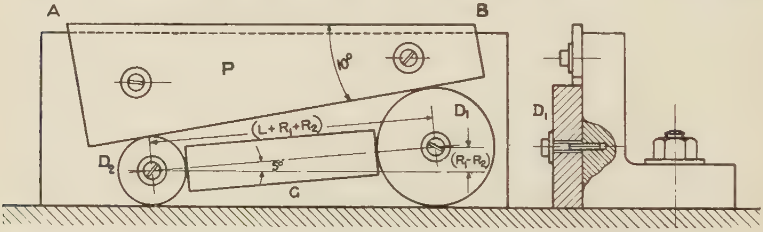


FIG. 163.

$$\sin 5° = \frac{R_1 - R_2}{L + R_1 + R_2} = \frac{0{\cdot}375}{L + 1{\cdot}375},$$

whence $$L = 0{\cdot}375 \operatorname{cosec} 5° - 1{\cdot}375 = 2{\cdot}9276 \text{ inches.}$$

The discs and plate P could be fastened to the angle plate by screws passing through loosely-fitting holes as shown, care being taken that firm contact occurred between the various parts before the screws were finally tightened. The upper surface AB of the plate could then be ground, and, if the surface of the table of the machine is true, the angle of the plate would be 10° as required.

---

* See *Annual Report of N.P.L.*, 1921, p. 117.

† *Ibid.*, 1923, p. 126; also p. 311 of this book.

The accuracy of the angle is determined principally by that of the diameters of the discs and the length of the gauge used. Since these can be determined without any difficulty to ±0·0001 inch, the angle should not be in error by more than ±10 seconds of arc.

Instead of discs of different sizes, a pair of equal ones could be used; one of them is then raised on a pile of block gauges, as in Fig. 164. In this case, if the diameter of the discs is D, the length of the separating gauge L, and the height of one disc above the other h, we have

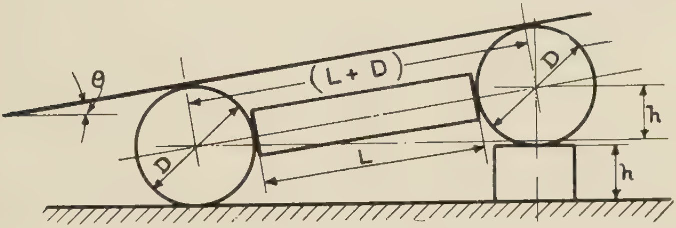


FIG. 164.

$$\sin \theta = h/(L + D).$$

Given θ, h and the size of the discs, it is therefore a simple matter to determine the length of gauge required.

(iii) **Adjustable Taper Gaps.**

The type of gauge shown in Fig. 165 is sometimes used for testing taper plug work. It consists of a pair of hardened steel plates A with straight edges, which are mounted on a base B having a slot along the middle. The angle and distance between the edges of the plates can be varied within the range of the slotted holes. The gauge can be set either by reference to a master tapered plug, as in the diagram, or by the use of a pair of discs and block gauges as described above. Work is tested by inserting it in the gap and viewing its fit against the edges of the side plates with light shining from behind through the slot in the base. To compare the diameters of the work with that of a master plug, the distance to which they can be inserted in the gap is noted against either the ends of the side plates or a line scribed on their faces. If desired, a pair of lines as at C can be used as limits.

This type of gauge is made by Messrs. Taft-Peirce, U.S.A.

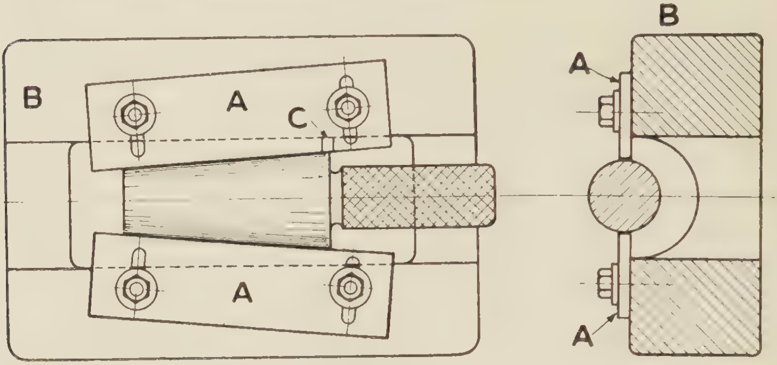


Fig. 165.

(iv) **Squares.**

Probably the commonest angle-testing appliance is the "square", which, as the name implies, is used only for checking right angles. The ordinary try-square has a rectangular stock carrying at one end a blade, the parallel edges of which should be set accurately at right angles to the stock.

A square can be used to a higher degree of accuracy if the edges of the blade are bevelled, as in Fig. 166. Contact with the piece being tested then takes place practically along a line, and small departures from squareness can be observed if the square is used against a well-lighted background.

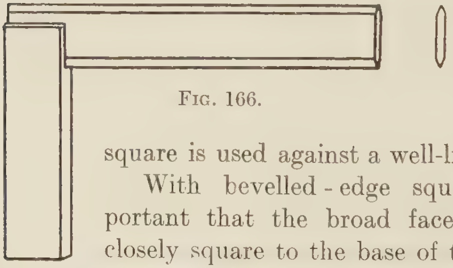


Fig. 166.

With bevelled-edge squares it is particularly important that the broad faces of the blade should be closely square to the base of the stock in the transverse direction. The significance of this will be appreciated if one considers testing the squareness between the base and the sides of a cylinder, as in Fig. 167. Any canting of the blade, as indicated in the right-hand diagram, will tend to give rise to an erroneous impression as to the squareness; even if the cylinder be true, light will be visible between its side and the edge of the square. Moreover, if the stock of the square be inclined from one side to the other in plan view, the magnitude and direction of the apparent lack of squareness will be seen to change. In such a test as this, it is preferable to use an ordinary square without a bevelled edge; even though the blade might be slightly bent, the trouble referred to would no longer arise. The sensitivity of test will hardly be diminished, since line contact will still tend to take place between the cylindrical surface and the flat edge of the blade.

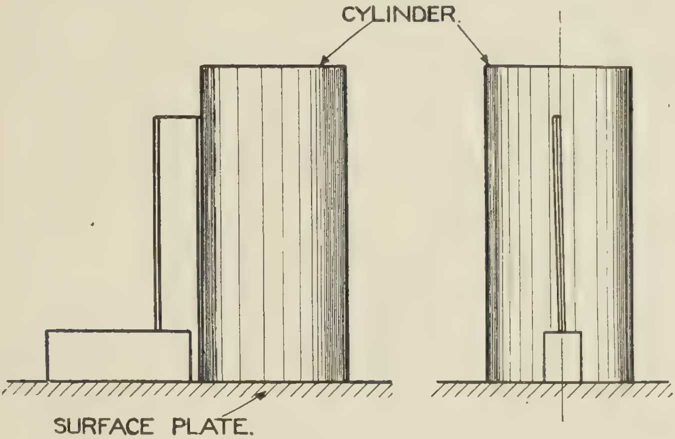


Fig. 167.

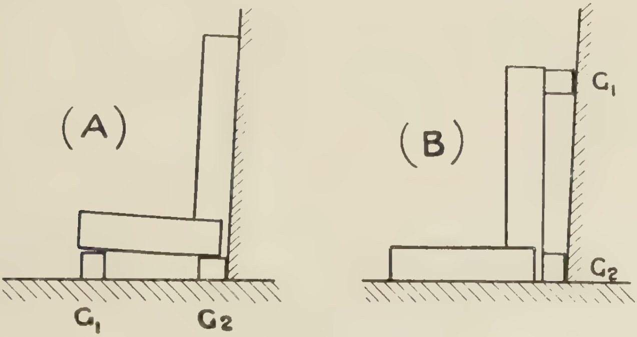


Fig. 168.

Occasions may arise when it is required to ascertain the actual extent of an error in squareness. Whilst approximate ideas can be obtained by visual estimates of the gap seen at one end or the other of the blade of the square, it will be found that much more reliable results can be obtained by the use of block gauges, as indicated in Fig. 168. The gauges can be used either as at (A) to tilt the stock of the square until the edge of the blade becomes parallel to the surface being tested, or they can be applied between the blade and the surface as at (B). In either case, the error in squareness can be expressed as the difference between the two gauges divided by the distance between their centres. This can readily be converted into minutes of arc by remembering that an angle of one minute is very closely equivalent to 0·0003 inch at a radius of an inch. (More exactly, 1 minute = 0·0002909 radians.)

It is important that squares should be tested periodically for accuracy. There are various methods of doing this. The traditional test is analogous to the mutual verification of three surface plates, and requires at least one, and preferably two, additional squares. Where three squares are available, their external angles can be compared by placing them back to back upon a good surface plate, using each pair in turn. If each test proves satisfactory, each square may be taken as correct. On the other hand, if one or more of the tests shows disagreement between the squares, the errors in the angles of the individual squares can be determined by adopting the method of Fig. 168 above. Thus, if the angles of the squares be denoted by A, B and C, and if a_1, a_2 and a_3 be the measured angles between the blades when tested in pairs, we have

$$\begin{aligned} A + B + a_1 &= 180^\circ, \\ B + C + a_2 &= 180^\circ, \\ C + A + a_3 &= 180^\circ. \end{aligned}$$

In writing down these equations care has to be taken to give a + or − sign to the small measured differences according to whether the blades are closest at the bottom or top respectively. From these three equations the values of A, B and C can then be found as follows :

$$\begin{aligned} A &= 90^\circ + \tfrac{1}{2}(a_2 - a_1 - a_3), \\ B &= 90^\circ + \tfrac{1}{2}(a_3 - a_1 - a_2), \\ C &= 90^\circ + \tfrac{1}{2}(a_1 - a_2 - a_3). \end{aligned}$$

Where only two squares are available, a similar procedure can be adopted by using the inner angle of one of the squares in place of the third one. The comparison between the inner and outer angles of the one square is made by testing the individual parallelisms of its stock and blade.

There are other methods, however, by which a square can be tested without the assistance of other squares. These methods have the additional advantage of giving more direct results than the one just described. The arrangement shown in Fig. 169, for example, enables a square to be checked against itself. The appliance is essentially an adjustable square consisting of a base-plate A, carrying at one end an upright bar B, to one face of which are screwed two accurately equal discs C. The square to be tested is placed, as shown, with its blade against one side of the discs, which are both brought into contact with it by tilting the base of the appliance about the two ball-ended feet D by adjusting the set-screw E. It is to be noted that the diameters of the discs are purposely made larger than the width of the upright bar, in order that their contact with the blade of the square can be observed against a lighted background. Having made the setting, the square is transferred to the opposite side of the discs, as shown dotted. Any error which may be present in the square is then revealed by lack of contact with one or other of the discs. The actual value of the error can be measured by using a micrometer screw at E, cognizance being taken of the fact that the error becomes doubled by reversal of the square. Needless to say, the discs should be separated as far as the length of the blade will permit, and to enable this to be done for squares of different sizes, the upright bar can be slotted or tapped with a series of holes, as shown.

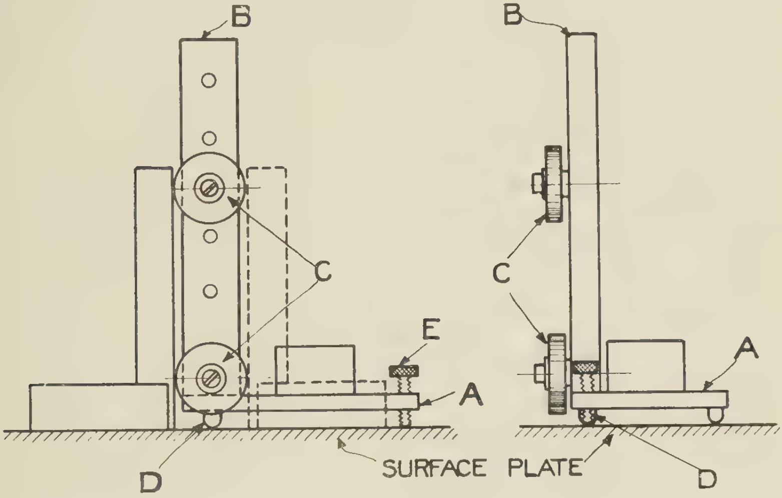


Fig. 169.

An apparatus on this principle has been designed and constructed at the National Physical Laboratory. A description of it is given in the Annual Report for 1928, p. 177. It was found to be an advantage to replace the two discs C by a steel plate having its edges ground and lapped accurately parallel.

It is clearly important that the surface plate used in conjunction with this test should be quite accurate.

This scheme of testing a square by reversal is utilized also in a method devised by G. A. Tomlinson of the National Physical Laboratory. The square is laid upon a surface plate with its stock against a fixed straight-edge of known accuracy. Lines are carefully scribed along the outside edge of the blade at the top and bottom on two small pieces of smoked glass G, held down on the surface plate with plasticine or soft wax (Fig. 170). The square is

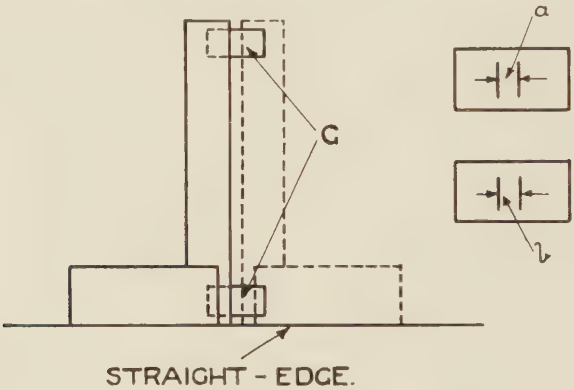


Fig. 170.

then reversed and two more lines are scribed in a similar manner about $\frac{1}{20}$ inch away from the others. The two glass plates are then removed and a comparison is made between the distances *a* and *b*, separating the pairs of lines, by measurements made in some form of travelling microscope or optical projection apparatus.* Equality between the two distances denotes absence of error in the square. On the other hand, should a difference be found, one half of it represents the departure from true squareness over the length of blade tested. No difficulty arises in deciding the direction of the error, providing a note is made connecting the position of the square with the lines scribed.

It need hardly be stated that, when scribing the lines, care has to be exercised to avoid parallax with respect to the edge of the blade. The scriber used should take the form of a chisel-blade, the flat face of which should be kept in contact with the edge of the square, and the glass plates should be packed up so that their surfaces are practically in contact with the underside of the blade.

---

* The horizontal projection apparatus described in Chapter XI. is very convenient for this purpose.

(v) Angle Plates.

The ordinary angle plate is a familiar accessory in any machine shop or tool room. Such plates are generally made of cast-iron, and are machined on the two outer faces and the edges.

To avoid subsequent distortion, they should be artificially aged by heat treatment after rough machining. The plates are usually slotted on the faces, as in Fig. 171; this enables them to be bolted to the table of a machine, whilst the work can be attached to the other face.

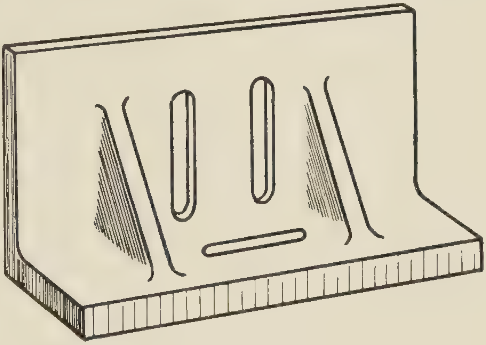


Fig. 171.

(vi) Block Squares.

Many uses can be found in machine shops and test rooms for block squares of the type shown in Fig. 172. These blocks are machined (preferably by grinding) on all the outer faces, so that they are mutually square in the three directions and opposite faces are parallel. For many purposes it is desirable to have such blocks in pairs, in which case they should be machined together so as to ensure equality of size. Incidentally, the addition

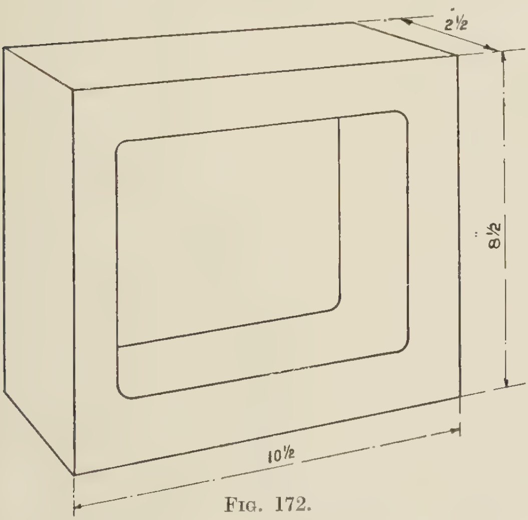


Fig. 172.

of a second block enables them to be checked for squareness one against the other.

The hollow section is desirable, as it enables work to be attached to one or other of the faces with an ordinary C clamp. In addition, the blocks can be readily held down on a surface plate or machine bed with finger clamps.

(vii) Reference Block for Squares.

In tool rooms it is desirable to have a reference block against which squares can be tried periodically and, if necessary, adjusted. A simple method of making such a standard is to grind a hardened steel cylinder (Fig. 173) on a mandrel so that it is parallel from end to end, and to face off the ends at the same setting. It is as well to relieve the end faces, leaving only a narrow seating round the edge; when placed on a good surface plate, the cylinder will then be quite free from any tendency to rock.

The verification of such a standard is merely a matter of checking the parallelism of the cylindrical surface—a test which can be carried out in any form of end gauge comparator capable of indicating differences of the order of 0·00005 inch. Even if any slight error in parallelism be present, it is to be remembered that only one-half will appear along any particular generator when testing a square.

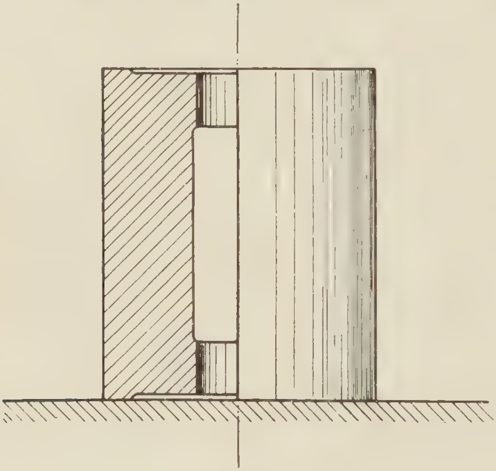


Fig. 173.

(viii) Sine Protractor.

Returning to instruments for setting out *any* angle, we come to a class the use of which is based upon the application of a trigonometrical ratio (usually the sine) of the angle required.

The instrument shown in Fig. 174 is similar to a bevel protractor in that it has a pair of straight-edges hinged together at one end, but the method of setting the blades at any required angle is entirely different. Each blade has attached to it, towards the free end, a semi-cylinder of half an inch diameter. When the two blades are brought together so as to become parallel, the measurement across the two halves of the cylinder is exactly half an inch.

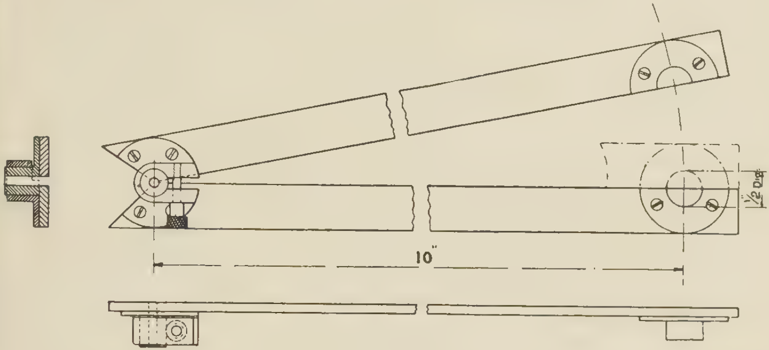


Fig. 174.

To set the blades to an angle θ, they are opened until a micrometer measurement across the semi-cylinders becomes equal to half an inch plus 2L sin $\theta/2$, where L is the distance between the centre of rotation of the blades and that of the semi-cylinders. By making L equal to exactly 5 or 10 inches, the arithmetical work involved becomes very simple.

(ix) **Sine Bar.**

Another device, known as the sine bar, for setting out angles by linear measurements, is shown in its simplest form in Fig. 175. It consists of a hardened steel bar of uniform width with two

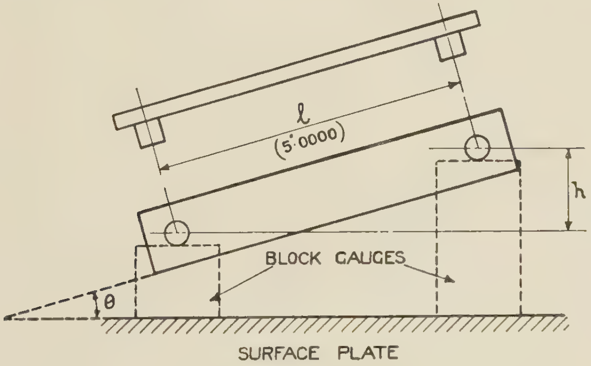


Fig. 175.

plugs of equal diameter inserted in it in such a manner that the line joining their centres is accurately parallel to the edges of the bar. The method of using the device is indicated in the diagram. To set the bar at an inclination θ to a surface plate, the plugs are raised upon two piles of block gauges, the difference in the heights of which (h) divided by the centre distance between the plugs is equal to sin θ. As in the instrument described above, the calculation of h for a given angle is facilitated by spacing the plugs exactly 5 or 10 inches apart.

Before entering into details of the different patterns and designs of sine bars, it may be of interest to ascertain the effect produced upon the angle by the presence of errors in the essential dimensions of the bar and in the setting up.

Lack of equality of the plugs or of their distances from the edges of the bar clearly has a direct effect upon the angle. If the difference between the radii or the distances of the centres of the plugs from the working edge of the bar be denoted by δ, the error in the inclination of the working edge will be equal to δ/l, where l is the distance between the centres of the plugs. In a 5-inch sine bar, for example, if δ is equal to, say, 0·0001 inch, the error in angle is of the order of 0·07 of a minute. Thus, δ could become as large as 0·0015 inch before the angular error would amount to as much as a minute of arc.

Turning now to the fundamental formula

$$\sin \theta = h/l,$$

by differentiating, we get

$$\cos \theta \,.\, d\theta = \frac{dh}{l} - \frac{\sin \theta}{l} \,.\, dl,$$

$$\therefore d\theta = \frac{\sec \theta}{l} \,.\, dh - \frac{\tan \theta}{l} dl.$$

Consider a 5-inch sine bar in which the error in the height h and in the distance between the plugs l is, say, 0·0001 inch in each case. We then have

$$d\theta = \pm 0{\cdot}00002 \sec \theta \mp 0{\cdot}00002 \tan \theta.$$

The error in θ due to each individual term is given in Fig. 176, for values of θ up to 90°. The upper curve corresponds to dh, and the lower one to dl. It will be seen that the two curves are practically the same, so that if dh and dl are of the *same* sign, the combined effect on the angle will be less than 0·1 minute for any value of θ. On the other hand, if their signs are opposite, the individual errors will be additive and will become rather appreciable, especially for angles approaching 90°. For instance, at 89° the error would be about 8 minutes.

From the general shape of the curves it is clear that the angle of setting becomes more and more susceptible to errors in h and l as the angle increases. At 90°, of course, accuracy of setting vanishes entirely. It is for this reason that, when using a sine bar for angles approaching 90°, it is desirable to abandon vertical measurements on the plugs, and to transfer them to a horizontal direction, making the necessary calculation from the complement of the angle. To do this, the measurements have to be made off the face of a true 90° angle plate, as at *h′* in Fig. 177, unless, as is sometimes the case, the bar is mounted on a fixture which can be turned through a right angle. If this course be adopted, and the general dimensions of the bar and the methods of setting it up are accurate to within 0·0001 inch, it may be taken that a 5-inch sine bar can be used to an accuracy of the order of ±10 seconds of arc. With the same permissible errors, a 10-inch bar can be relied upon to give angles true to ±5 seconds.

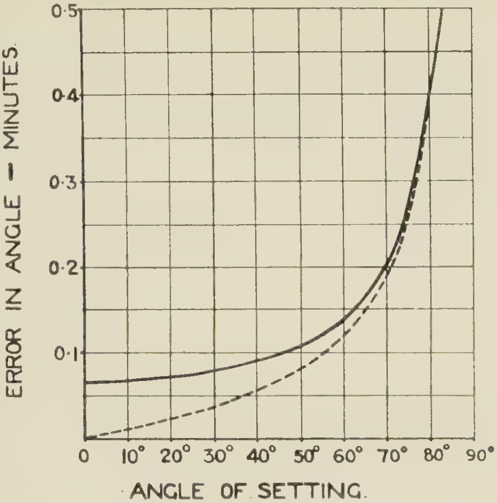


Fig. 176.

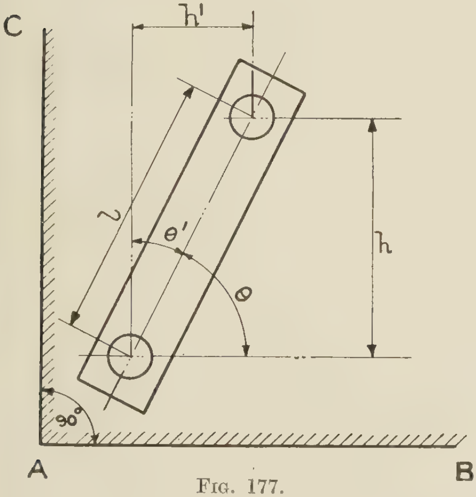


Fig. 177.

There are several designs of the sine bar even in its simplest form. The Johansson pattern, Fig. 178, is

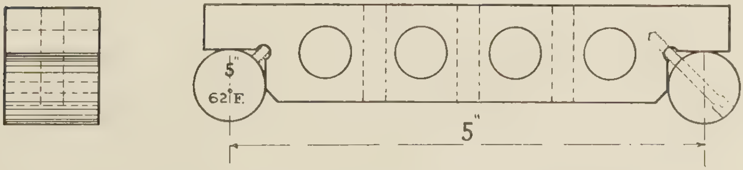


Fig. 178.

stepped at the two ends to form seatings for the cylinders which are screwed to the bar. This method of manufacture enables the cylinders to be readily adjusted to the desired distance apart and to be parallel to the upper and lower faces of the bar. The three holes in the bar enable it to be bolted to an angle plate, otherwise there is no means of holding the sine bar in position.

A type of sine bar made by the Pitter Gauge Company presents certain novel features which will be gathered from Fig. 179. The bar, which is of 10-inch size, is hinged at one end to a substantial, hardened steel block by a well-fitting pin, whilst another block of lighter proportions is hinged on a corresponding pin at the other end. The lower faces of these two blocks are lapped to a wringing finish, the distances A from the centres of the pins being made exactly equal. The upper end of the bar is slotted so as to enable the pins to be spaced accurately at 10 inches.

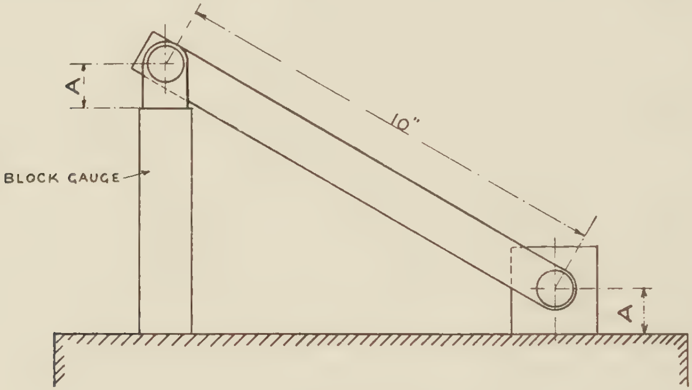


FIG. 179.

Only one pile of block gauges need be used with this type of sine bar, which possesses the additional advantage of requiring no auxiliary support beyond the surface plate to which the base block is wrung.

A typical application of the sine bar principle is illustrated in Fig. 180, which also shows the Pratt and Whitney form of sine plate. The tapered plug gauge under test is mounted on centres supported on a sine block. The latter consists of a cast-iron plate resting on a pair of cylinders located in parallel vee-grooves in its base. The inclination of the gauge is adjusted by placing block gauges beneath one of the cylinders until the upper side of the cone on the gauge becomes parallel to the surface plate, as tested by a sensitive indicator. The exact angle of the cone can then be readily calculated from the size of the block gauges used and the distance between the supporting cylinders.

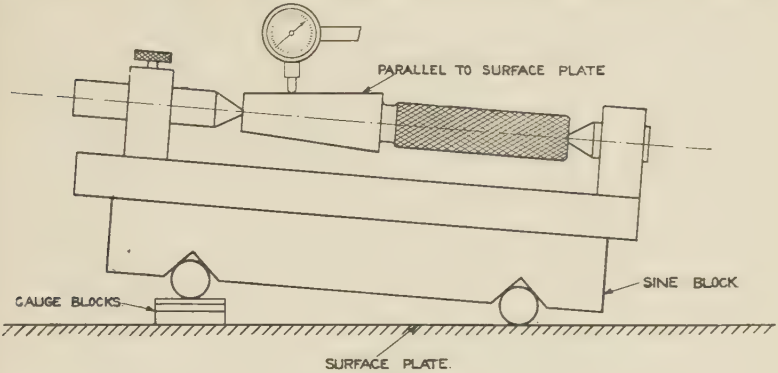


FIG. 180.

The Taft-Peirce sine bar fixture, Fig. 181, consists of a 5-inch bar with the usual plugs, mounted on a slotted bracket above a finished base plate. The height of the bar above the base can be adjusted and clamped independently of the clamping for the sine bar itself. A pair of knurled-headed screws on the supporting arm provide fine adjustment for the angular position of the bar.

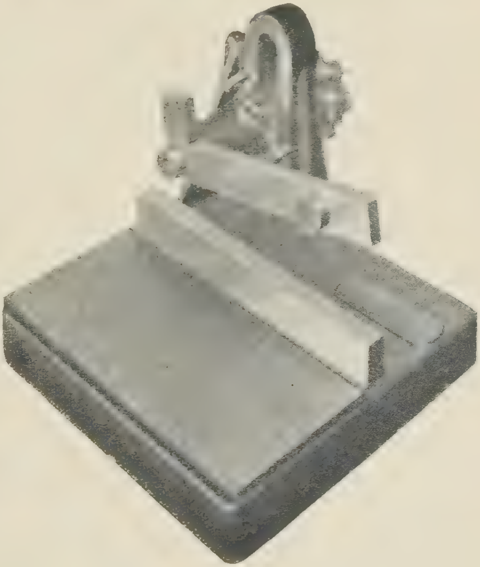


FIG. 181.

The left-hand edge of the bracket and the side of the base plate are finished square to the base plate and the plane of the sine bar, so that when required the whole fixture can be turned over upon its side. This feature is particularly useful when the sine bar has to be set at an angle greater than

45° with the base. Ordinarily, this involves some loss of accuracy, but by placing the fixture on its side the setting can be made from the complement of the angle required (see p. 153).

The adjustable angle plate, Fig. 182, made by the same firm, is designed chiefly for setting up work for machining, but can be used to equal advantage for inspection purposes. The inclination of the adjustable table can be read directly to 5 minutes of arc by means of a circular scale and vernier on the rear quadrant of the base. If required, closer accuracy can be obtained by utilizing the sine-bar attachment incorporated on the front quadrant. One of the plugs forms an extension of the pivot for the table, whilst the other is attached to the side of the table at the usual radius of 5 inches. The base itself is finished accurately square on the bottom and side, so that large angles can be dealt with by the sine method without any sacrifice of accuracy. The table has a surface 7 × 10 inches, and is provided with T-slots as shown. For the highest accuracy, the height of the movable stud would be set by means of block gauges instead of a vernier height gauge as in the illustration.

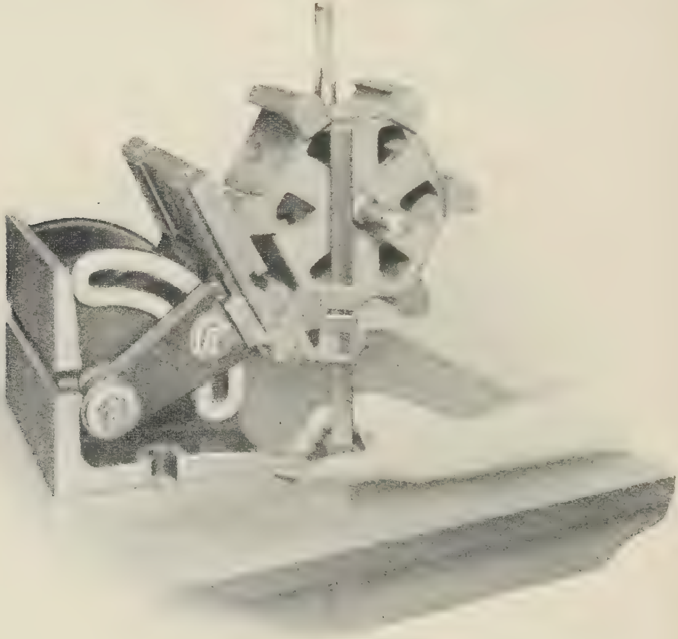


FIG. 182.

In addition to the arrangement of a simple sine bar as in Fig. 179, the Pitter Gauge Company have developed the sine-bar fixture shown in Fig. 183. This, like all sine-bar arrangements, enables angles to be set out or measured to a high degree of accuracy, but, besides this, it greatly facilitates the measurement of distances in angular directions.

The arrangement itself is quite simple. The sine bar, which is provided with a short right-angle arm as in the Taft-Peirce type (see Fig. 181), is pivoted at the elbow to a massive steel block, which is accurately machined all over. The height of the pivot above the base is known, and the angular setting of the bar is made, as usual, by inserting a pile of block gauges of the necessary height beneath the measuring plug at the end of the bar.

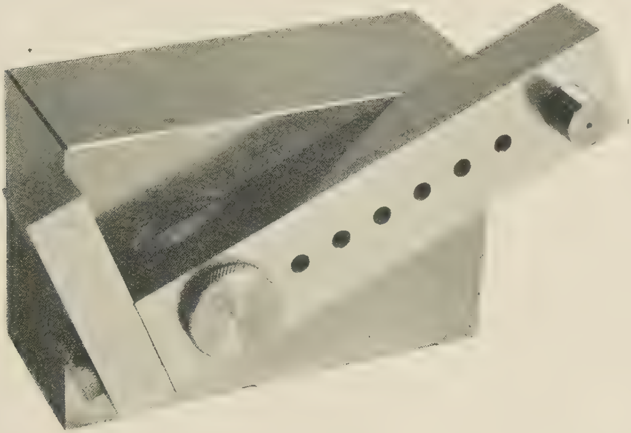


FIG. 183.

As an illustration of the uses of this fixture, by means of which templates can be checked solely with block gauges, we will consider the testing of a template ABCDE, as in Fig. 184. The dimensions and angles to be ascertained are a, b, c, α and β. Assuming that a preliminary test shows all the edges to be straight and the two sides BC and DE accurately square with the base DC, the template is placed upon the sine bar, and the angle of the latter, and the size of a combination of block gauges G_1, are adjusted so as to bring the edge AB at a definite height, g_2, above the upper surface of the block. This is tested with a knife-edge straight-edge, or an indicator, against the surface of a gauge G_2, of thickness g_2, which is wrung on to the block.

The angle α is then obtained by measuring the inclination of the bar in the usual manner, whilst the dimension a can be found from the relation :

$$h+g_2=d+(a+f)\cos\alpha+(g_1+b-e)\sin\alpha.$$

The angle β and dimension c can be measured in a similar manner by turning the template end for end. It is to be noted that the dimensions d, e, f and h are constants relating to the fixture, and can be ascertained by simple measurements once and for all.

Although the above procedure may need to be varied at times, the general principle will remain the same.

It should be understood that the fixture can also be used to equal advantage during the actual machining of templates. In this case the angle of the sine bar and the gauges used as distance pieces are set to suit the required dimensions, after which the upper edge of the template is ground down to within a definite height above the top of the block, as checked with a gauge and a straightedge. Tapped holes are provided in the sine bar for clamping screws to hold the work against the face of the block during the machining.

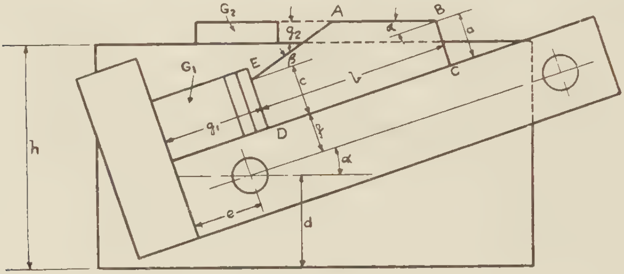


FIG. 184.

This sine bar and the supporting block are made of hardened steel and all the important surfaces have a lapped finish, so that block gauges used in conjunction with the apparatus can be brought into wringing contact with it.

ADDITIONAL REFERENCES FOR CHAPTER VII

"Optical Methods of Setting Work and Tools," *Machinery*, vol. 28, p. 97 (1926).

"Linear and Circular Dividing Machines for Laboratory and Works," Catalogue No. 360, issued by La Société Genevoise.

"Circular Dividing Machine" (La Société Genevoise), *Amer. Mach.*, vol. 62, p. 216 (1924).

"Precision Level" (La Société Genevoise), *Amer. Mach.*, vol. 60, p. 671 (1924).

"Circular Dividing Engine of Troughton, 1793," *Trans. Optical Soc.*, vol. 25, p. 135 (1923–24).

"Untersuchungen an einer Kreisteilmaschine," L. Fritz, *Zeit. für Instrument.*, vol. 46, p. 289 (1926).

"Improved Universal Dividing Head," *Amer. Mach.*, vol. 47, p. 171 E (1918).

"Universal Knee for Marking-Off," E. Lytton-Brooks, *Amer. Mach.*, vol. 62, p. 117 E (1925).

"Die Genauigkeit von 90° Stahlwinkeln," Dr. G. Berndt, *Zeit. für Feinmech. und Präzision*, vol 35, pp. 279, 295 (1927).

Self-Checking Square, Booklet No. 11, issued by Cambridge Inst. Co.

"Square Testing Device," S. A. Inscoe, *Amer. Mach.*, vol. 52, p. 32 E (1920).

"Improved Universal Dividing Head" (J. Parkinson and Son), *Amer. Mach.*, vol. 47, p. 171 E (1917).

"Universal Angle Plate," R. Bernhardson, *Amer. Mach.*, vol. 47, p. 736 (1917).

"Johansson Angle Slips," *Amer. Mach.*, vol. 51, p. 669 (1919).

"Checking Angles with Swedish Blocks," H. B. Lewis, *Amer. Mach.*, vol. 47, p. 353 (1917).

"The Sine Bar in Machine Work," Hugo Pusep, *Amer. Mach.*, vol. 46, p. 995 (1917).

"Slocum Sine Bar and Indicating Square," *Amer. Mach.*, vol. 47, p. 567 (1917).

"Uses of the Sine Bar," E. J. Bryant, *Amer. Mach.*, vol. 47, p. 749 (1917).

"Sine Bar Gauge for Large Work," *Amer. Mach.*, vol. 61, p. 60 (1924).

"Improved Sine Bar," *Amer. Mach.*, vol. 45, pp. 77, 342, 869 (1916).

"Sine Protractor," Blomstrom, *Amer. Mach.*, vol. 45, p. 340 (1916).

"Accurate Sine Bar," Henke, *Amer. Mach.*, vol. 45, p. 1032 (1916).

"'Simplex' Sine Bar," *Amer. Mach.*, vol. 45, p. 656 (1916).

"Accurate Angle Measuring Device," E. A. Dixie, *Amer. Mach.*, vol. 52, p. 835 (1920).

"The Use of the Sine Bar," *Machinery*, vol. 19, p. 529 (1921–22).

"Calibration of Level Tubes," *Report of N.P.L., 1921*, p. 139.

"Untersuchungen von Sekundenlibellen," B. Wanach, *Zeit. für Instrument.*, vol. 46, p. 221 (1926).

"Spirit Levels in the Machine Shop," E. F. Creager, H. L. Wheeler, *Amer. Mach.*, vol. 62, pp. 160, 528 (1925).

"Spirit Levels," E. O. Henrici, *Trans. Opt. Soc.*, vol. 20, p. 45 (1918).

"Adjustable Spirit Level," *Amer. Mach.*, vol. 56, p. 128 E (1922).

Surveying Instruments, Abraham (published by Casella, London, 1926).

"Levels and Level Bubbles," S. G. Starling, *Trans. Opt. Soc.*, vol. 24, p. 261 (1922).

"Spirit Levels," Paper by S. Weston and V. Towns before Optical Convention (1926).

"Grinding and Testing Level Vials," G. N. Saegmuller, *Amer. Mach.*, vol. 56, p. 405 (1922).

"New Types of Levelling Instruments using Reversible Bubbles," T. F. Connolly, *Trans. Opt. Soc.*, vol. 25, p. 21 (1923–24); vol. 26, p. 194 (1924–25).

"A Double Reflection Level," D. S. Perfect, *Trans. Opt. Soc.*, vol. 30, No. 3 (1928-29).

"A New Autocollimator," F. E. Wright, *Jour. Opt. Soc. Amer.*, vol. 9, p. 187 (1924).

"Accurate Angles by Optical Methods," F. C. Hudson, *Amer. Mach.*, vol. 64, p. 601 (1926).

Methods of Machine Shop Work, F. A. Halsey (McGraw-Hill Book Co., 1914).

CHAPTER VIII

INTERNAL MEASUREMENTS

As a general rule, internal dimensions of work pieces are tested with limit gauges, various types of which are described in Chapter I. Where fine tolerances occur, or when it becomes necessary to test accurately the uniformity of the dimension, use is made of some form of internal measuring instrument or comparator.

In the examination of gauges, where the tolerances are usually of the order of only a few ten-thousandths of an inch, internal measurements have to be made to a correspondingly high degree of accuracy and, where extreme accuracy is required, have to be carried out on machines specially designed for that purpose. Descriptions of such machines are given in the following pages, together with other methods and appliances used in workshops, test rooms and laboratories for internal measurements.

The Use of Limit Gauges.

The limit gauges used for testing holes usually consist of a pair of plug gauges, the diameters of which are made respectively to the two limits for the work. The hole should accept the " go " gauge freely, whilst it should not be so large as to admit the " not go " gauge. When applying the " go " gauge, any tendency to force it into the work should be avoided ; if the fit is at all tight, the work should be rejected as being too small. Under certain conditions even a moderate pressure will enable a gauge to be inserted into a hole which is smaller in size by several ten-thousandths of an inch. The tendency for a hole to expand so as to admit a gauge under pressure depends upon the stiffness of the metal round the hole, the finish of the surface and the state of lubrication between the surfaces of the gauge and the hole. With lapped holes in particular, even a very light film of oil or grease between the gauge and work may lead to the acceptance of small holes.

In using a "not go" plug gauge, care has to be taken to see that the edge of the hole is free from burrs. This is one objection to the use of a "not go" gauge in the form of a cylinder. The same type of gauge is also likely to pass elliptical holes which are above the upper limit over a considerable portion of their surfaces. In addition, with a cylindrical "not go" gauge, it is impossible to test the hole throughout its length. As a rule, the tendency is for holes to be somewhat bell-mouthed, so that a "not go" test at the ends suffices. On the other hand, oversize holes might sometimes be intentionally closed in at the ends with the object of preventing the entry of the inspector's "not go" gauge.

A type of gauge which defeats such malpractice and which enables the hole to be tested across *any* diameter is shown in Fig. 185. By slightly canting the spherical-ended rod A, it can be inserted into the hole to test the diameter at any desired position.

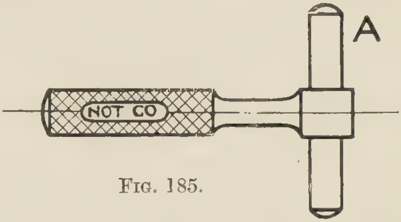


FIG. 185.

"Pin" Gauges.

A type of internal gauge frequently used in workshops consists simply of a steel rod, Fig. 186, with conical ends which are hardened

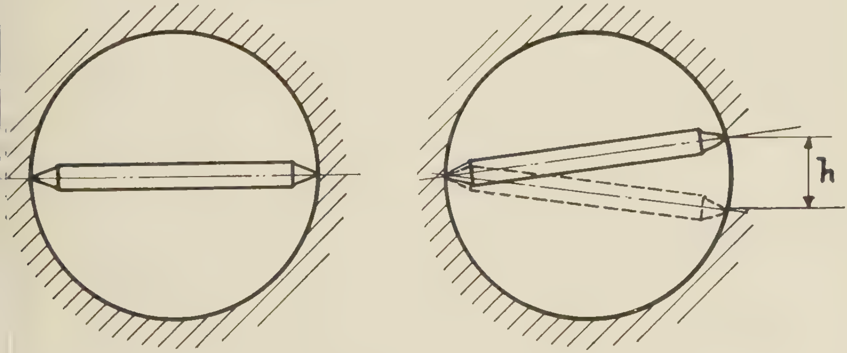


FIG. 186.

and rounded off to a small radius. No handle is fitted, but the rod is sometimes mounted in an insulating tube to minimize expansion due to the effect of handling. When required for testing the diameter of a recess close to a shoulder, the conical ends may be made as in Fig. 187.

These gauges are generally known as pin gauges. They are usually finished to size by stoning down the ends until the length is equal to the size of the hole required. The latter is then bored out until the rod is a comfortable fit in it. Occasionally they are made in pairs to act as limit gauges.

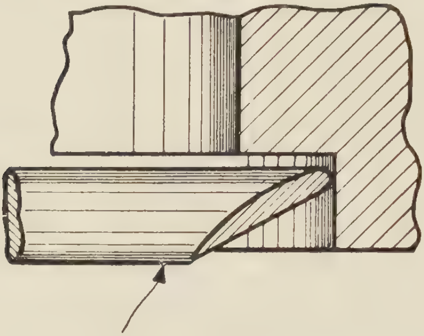


Fig. 187.

If only one gauge is used, and the hole happens to be bored so that the gauge is rather an easy fit in it, a fairly close estimate of the excess of the diameter over the length of the rod can be obtained by noting the amount of side play, h (Fig. 186), of one end of the rod in the hole. Denoting the length of the rod and the diameter of the hole by L and D respectively, then

$$(D - L) = \frac{h^2}{8L} \text{ (approximately).}$$

Thus, a $\frac{1}{4}$ inch of play at one end of a 12-inch rod would represent an approximate excess in diameter of 0·0006 inch.

The Use of Callipers.

With the aid of a pair of ordinary inside callipers and a micrometer, it is quite possible for an experienced operator to measure the diameters of holes, or internal distances, up to about 6 inches, to an accuracy of about 0·0001 inch. The callipers are carefully set by "feel" to the diameter of the hole or distance required, and the size over the legs is then measured between the faces of the micrometer. In making this measurement it is convenient to rest the micrometer on the bench and, with the callipers in one hand, to adjust the micrometer until the feel of the calliper between its faces is the same as when originally set to the work.

Folding Wedges.

A pair of folding wedges, Fig. 188, if carefully made, will enable the diameters of holes to be measured to about 0·0001 inch. The diameter D may be measured directly over the wedges where they project beyond the hole, or it can be derived from a measurement M taken over the ends of the two pieces. In the latter case, it is necessary to calibrate the wedges by correlating a series of measurements D and M. This may be done by inserting the wedges in a number of standard ring gauges, or in gaps built up from block gauges.

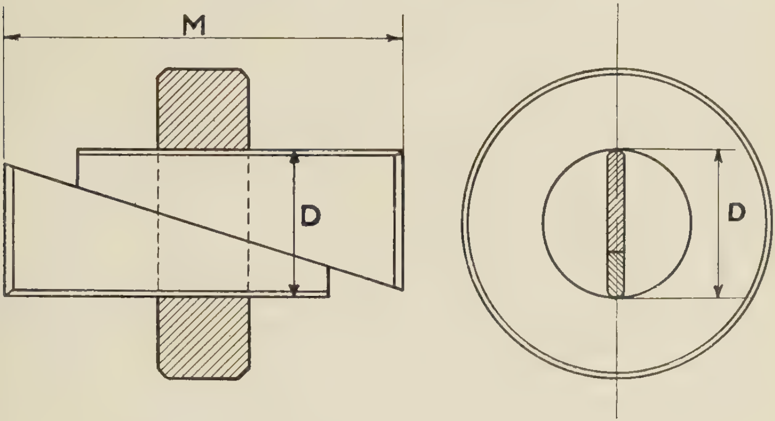


Fig. 188.

It is obvious that the accuracy of determination of the diameter D from a measurement M can be increased by reducing the angle of the wedges. The smaller the angle, however, the more restricted becomes the range of diameters covered by a particular pair of wedges. An angle of one in five is found to be a convenient value for practical purposes.

Such wedges should be of hardened steel, and can readily be produced in a tool room to the necessary accuracy. A set of ten wedges covering all sizes from $\frac{1}{4}$ to 1 inch is obtainable from Messrs. Brown and Sharpe.

The Use of Block Gauges for Internal Measurements.

When first introducing block gauges, Messrs. Johansson extended their use to internal measurements by the provision of auxiliary pieces A, Fig. 189, which could be wrung on to the ends of a gauge, or a combination of gauges.* The outer faces of the projecting portions of these jaws, or " points ", are ground cylindrically so that the thickness t is some convenient figure such as 0·1, 0·2 or 0·25 inch † to within a few hundred-thousandths of an inch, thus making it a simple matter to ascertain the distance D over the projections from the sizes of the included gauges.

---

* See also Vol. I. p. 77.

† The jaws are also made in metric units.

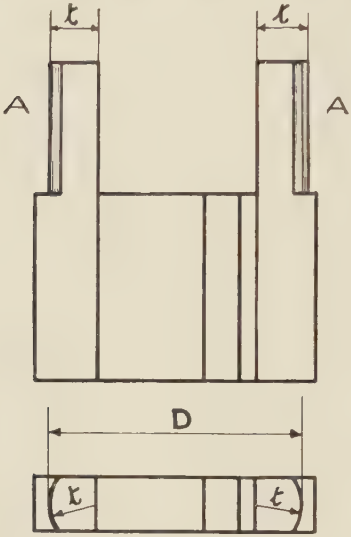


Fig. 189.

When in use for measuring a hole, the block gauges and jaws are wrung together and mounted in a holder, Fig. 190, in which they are rigidly clamped together by the screw shown. The process of measurement consists in varying the sizes of the block gauges by steps of 0·0001 inch until a nice fit is obtained.

Using the smallest size of jaws in conjunction with a special set of thin slip gauges, it is possible by this method to measure holes down to about $\frac{1}{4}$ inch in diameter, to an accuracy of 0·0001 inch.

Instead of wringing jaws on to the ends of block gauges, the latter can also be used in conjunction with a pair of cylinders of known size, as in Fig. 191. Hoffmann Roller Gauges* are very convenient for this purpose. Here, again, the size of the block gauge combination is adjusted until it can just be introduced between the cylinders without forcing. This will give the size of the hole to

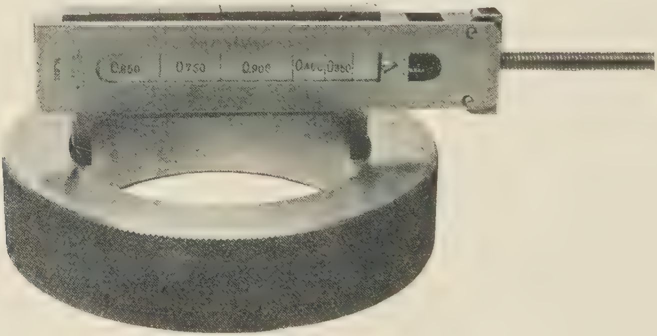


Fig. 190.

---

* See p. 89; also Vol. I. p. 120.

within 0·0001 inch. If a closer measurement is required, it can be obtained by observing the arc of freedom, h, of one of the cylinders, keeping the other one fixed. If the mean diameter of the cylinders is D, and the length of the block gauges J, then the diameter of the hole is very closely equal to

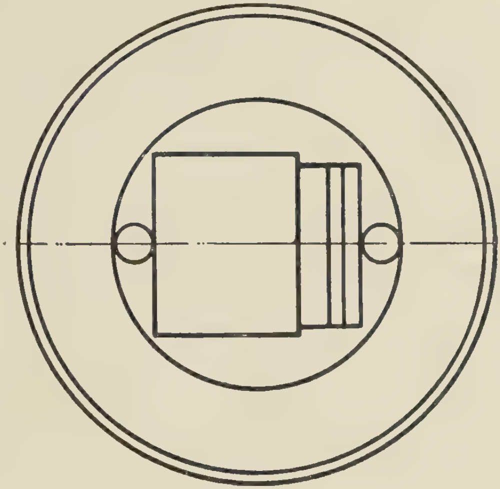


FIG. 191.

$$J + 2D + \frac{h^2}{8(J + D)}.$$

For example, if $J = 1{\cdot}25$, $D = 0{\cdot}5$ and $h = 0{\cdot}03$ inch, then the excess of the diameter of the ring over the sum $(J + 2D)$ is equal to 0·00006 inch.

The Use of Steel Balls.

In the absence of block gauges, accurate measurements of rings or holes can be made by the use of two steel balls of suitable sizes, as in Fig. 192. The gauge is placed upon a surface plate and a measurement is made of the height H by means of a micrometer height gauge. The diameter of the ring is then given by

$$\frac{D_1 + D_2}{2} + \sqrt{H(D_1 + D_2) - H^2},$$

where D_1 and D_2 are diameters of the balls.

It is clear that by choosing balls so that the height h between their centres is small the method becomes very sensitive. But on the other hand, the more nearly the sum of the diameters of the balls approaches that of the ring, the greater become the pressures at the three points of contact A, B and C due to the weight of the upper ball, and, in extreme cases, it may become necessary to take into account the elastic deformation at these contacts.

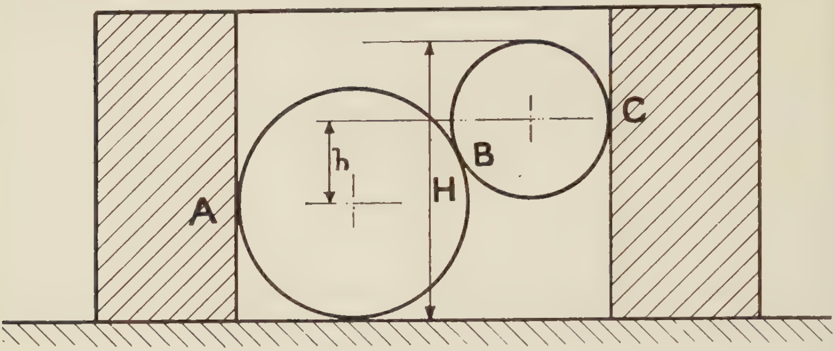


FIG. 192.

For larger rings it may be more convenient to use four balls, arranged as in Fig. 193. Knowing the sizes of the balls, the only measurement required is, as before, the height H of the central ball.

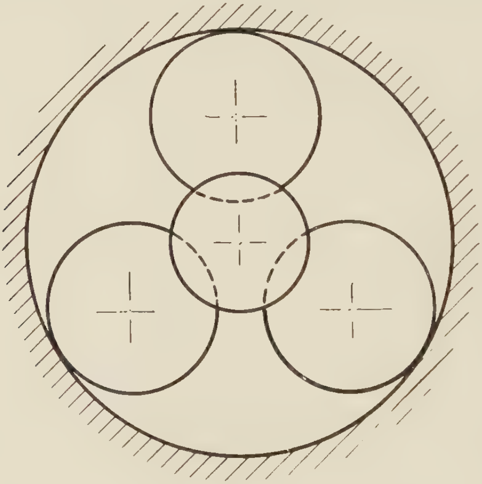


FIG. 193.

If D_1 is the mean diameter of the three lower balls and D_2 that of the central one, the diameter of the hole is given by

$$D_1 + 2\sqrt{H(D_1 + D_2) - H^2}.$$

The "Maire" Gauge.

Instead of using the upper ball, the separation between the three lower ones can be measured by inserting a tapered plug between them. This is the principle employed in the Maire gauge (Patent No. 8034-08). It consists of a tube A (Fig. 194), through which passes a loosely-fitting rod B, tapered at the left-hand end by 0·004 per inch, and graduated on the stem at the other. The three steel balls fit loosely in pockets in the boss C. In use, the rod is withdrawn sufficiently to allow of the boss being inserted into the ring, and the rod is then gently depressed until the balls are felt to make contact. The reading on the stem is then noted against a line on the tube.

The scale is graduated to read to 0.0002 inch, and is calibrated by taking readings on a number of standard ring gauges. One drawback to the instrument is its limited range, which is of the order of only 0·02 inch. This, of course, could be extended by using a steeper taper on the rod, but only at the expense of accuracy of measurement.

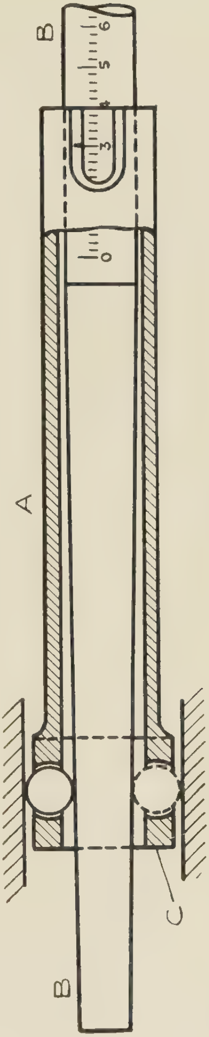


Fig. 194.

Expanding Plug Gauge (Taft-Peirce).

Another type of expanding gauge is shown in Fig. 195. Here the gauging members consist of four hardened steel blades A, with their inner edges seated upon a conical spindle attached to the handle B. The blades are located in a frame C by dove-tailed retaining blocks D. This frame can be moved axially with respect

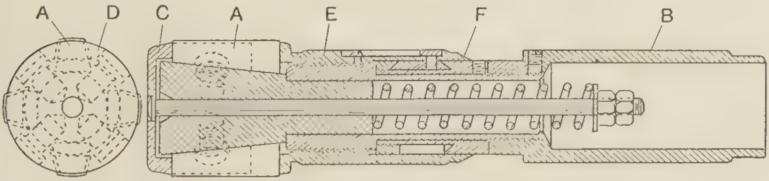


Fig. 195.

to the conical spindle by turning the sleeve E, which has an internal thread engaging with a 20 T.P.I. micrometer screw on the handle. The bevelled edge F of the sleeve is graduated to read to 0·0002 inch, and the total diametral range of the gauge is about $\frac{1}{16}$ inch.

When required for use as a limit gauge, adjustable stops can be brought into action which limit the travel of the sleeve in the two directions.

This gauge is manufactured by the Taft-Peirce Manufacturing Company, U.S.A.

Newall Internal Micrometer.

A type of internal micrometer, manufactured by the Newall Engineering Co., is shown in Fig. 196. It has three measuring plungers A with spherical ends, each capable of sliding in a tubular leg B, screwed into the body of the gauge. The plungers can be moved radially by the action of a coned spindle which makes contact with their inner ends. This spindle carries a micrometer screw at the other end, and its axial movements are recorded on a thimble C, graduated to read to 0·001 inch. Light compression springs are employed for maintaining contact between the plungers and the cone when the latter is withdrawn.

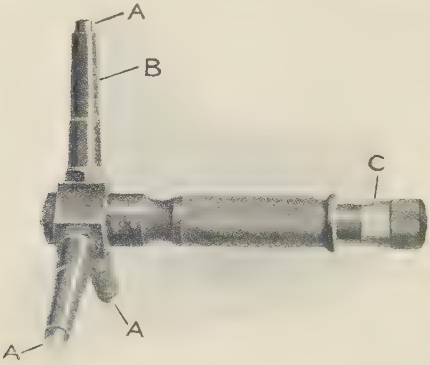


Fig. 196.

In order to increase the range of the instrument, the legs can readily be unscrewed from the body and replaced by other sets having measuring plungers of another length. Each set gives a half-inch range of measurement, which is increased to an inch for sizes above 9 inches. The smallest size will deal with holes down to 2½ inches in diameter. These micrometers are made in both inch and metric units.

Owing to the presence of the three contacts, the readings of this form of micrometer can only be checked for absolute size by taking observations on standard rings.

Inside Micrometer Callipers.

Holes between 0·2 and 2 inches diameter can be measured to an accuracy of 0·0001 inch by means of micrometer callipers of the

Brown and Sharpe pattern shown in Fig. 197. One of the measuring jaws is attached to the tubular body of the instrument and the other to a spindle, the axial movement of which is controlled by a 40 T.P.I. (or 0·5 mm. pitch) micrometer screw. The distance over the measuring faces can be read directly to 0·001 inch (or 0·01 mm.), from graduations engraved on the barrel and rotating thimble. The reading can be checked at any time by measuring over the faces with an ordinary micrometer.

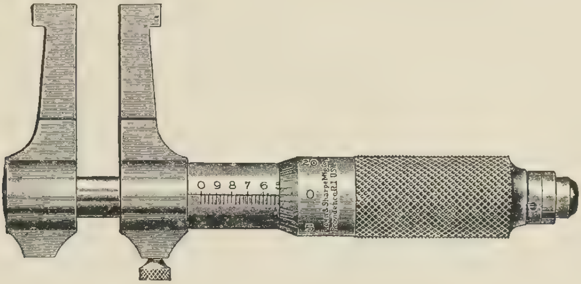


FIG. 197.

Inside Micrometers.

(i) *Brown and Sharpe Pattern.*—For large diameters, or distances, the rod type of internal micrometer, Fig. 198, is used. This consists of a holder carrying a micrometer screw with a range of $\frac{1}{2}$ or 1 inch.

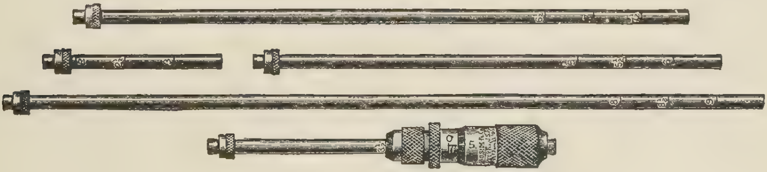


FIG. 198.

A series of extension rods is provided to enable measurements to be made over a considerable range. For example, the set shown has a range from 2 to $9\frac{1}{2}$ inches. Each rod is graduated by a series of angular grooves, spaced half an inch apart. When inserting a rod in the holder, it is gripped in position by a clamp, the fingers of which spring into one or other of the angular grooves. This provides a ready means of setting up the instrument to deal with any measurement within its capacity. The tips of the rods and the contact at the end of the micrometer thimble are hardened and slightly rounded.

After continual use, the zero setting of each rod should be checked by an overall measurement in a micrometer, or measuring machine, in order to detect wear.

This type of internal micrometer is made up to a capacity of 36 inches.

(ii) *Zeiss Pattern.*—Another type of internal micrometer set which includes a series of extension rods is that made by Messrs. Carl Zeiss, Fig. 199. The micrometer head, which is to be seen at the bottom right-hand corner of the set, has a range of half an inch and has a spherical contact at each end. In itself, it serves for measurements from $2\frac{1}{2}$ to 3 inches, but this range can be increased in the set illustrated, up to a maximum of 36 inches, by the addition to the micrometer of one or more of the extension rods. These rods have spherically-shaped ends, and each is enclosed in a tubular socket having an external screw at one end and an internal screw at the other, Fig. 200. When screwing the tubes together, or on to the micrometer, it is important to note that the ends of the rods are brought into contact under a uniform spring pressure, independent of the tightness with which the sockets are screwed together. When not in use, the ends of the rods are concealed within their sockets, and are thus protected from injury.

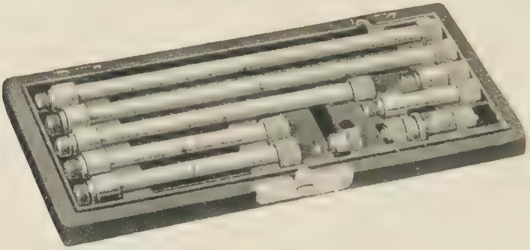


Fig. 199.

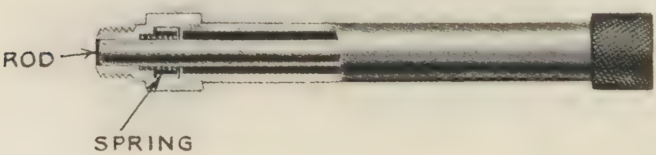


Fig. 200.

The micrometer has the usual 40 T.P.I. screw, and reads direct to 0·001 inch. The same type of instrument is made in metric units.

(iii) *Pitter Type.*—One of the latest forms of internal micrometer is that made by the Pitter Gauge and Precision Tool Co. A section through the gauge is shown in Fig. 201. The micrometer head A and the end-piece B have spherically-shaped contacts, whilst their inner faces are lapped flat and have a wringing finish. These two parts can be wrung on to the ends of distance pieces C, of length L, in the form of end bars. These consist of tubes with hardened steel terminal plugs, the faces of which are lapped to a wringing surface by a process similar to that employed in finishing the ends of this firm's well-known standard bar gauges.* The wringing joints ensure satisfactory contact between the three parts, but, in order to give the necessary mechanical strength, the parts are also held together by screwed studs D, which are made easy fits in their tapped holes so as not to disturb the alignment of the bars.

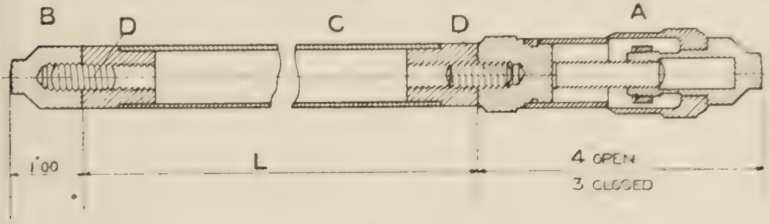


Fig. 201.

The distance pieces are supplied in the same series of sizes as is adopted by this firm for their set of workshop end bars, viz. 1, 2, 3, 4, 5, 6, 7, 8, 15, 23 and 31 inches. With the micrometer and end-piece B in contact, a minimum measurement of 4 inches is possible. By inserting the bars, either singly or in suitable pairs, it is possible to deal with any size between 5 and 44 inches. If three bars are used, the range can be extended still further to 67 inches.

The makers guarantee the accuracy of this gauge to be within one part in 100,000.

Indicating Instruments for Internal Measurements

(i) Hirth Minimeter Fixtures.

The Hirth Minimeter † tube has been adapted in several ways for the purpose of measuring ring gauges and holes. In every case the instrument serves only as a comparator, and has to be set up on a standard ring gauge of closely the same size as the hole to be measured.

---

* See Vol. I. p. 109.

† For description see Vol. I. p. 328.

The simplest type of fixture is that in which the tube is held in a frame provided with two ball-feet, as shown in Fig. 202. When setting the instrument to the standard gauge, a coarse adjustment is obtained by sliding the tube in its socket, whilst the final setting is made by means of the screwed feet. Needless to say, it is necessary to rock the instrument backwards and forwards whilst in a hole and to note only the minimum indication. When used in conjunction with extension pieces, this fixture will cover a range from 7 to 40 inches diameter.

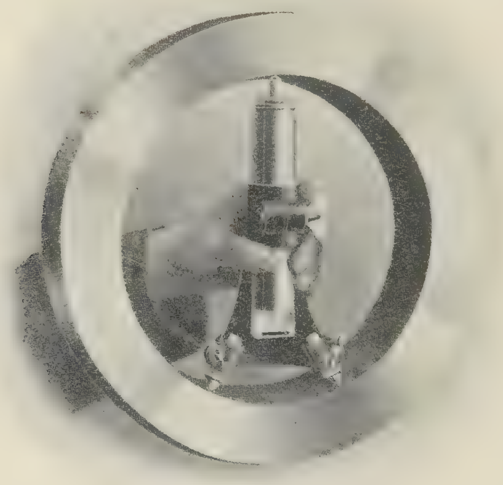


Fig. 202.

Another arrangement for measuring diameters from 2 to 4 inches is shown in Fig. 203. Here, again, two ball-ended contacts A are used for locating the ring, whilst the third, B, is attached to a horizontal lever, the other end of which operates the measuring plunger of the minimeter tube C. The positions of the two lower contacts can be adjusted to suit different sizes of rings by sliding the legs along the slots in the body of the instrument. The latter is also provided with facing strips against which the ring can be pressed, so that the measurement is made in a plane normal to its axis. Measurements can be made at various distances up to about $2\frac{1}{2}$

inches from the face of the ring by moving the body along the dovetailed slide and adjusting the projections of the legs in the slots.

For comparatively deep holes the arrangement shown in Fig. 204 can be used. The minimeter tube is mounted in a socket, the other end of which carries a head having three contact points. Two of these, AA, are screwed directly in the head, whilst the measuring contact B is screwed into a plunger which can slide in a bush. The motion of this plunger is transmitted to the minimeter through a bell-crank lever and a rod passing down the centre of the main stem. The fitting C serves to centralize the instrument in the hole, and its position on the stem can be varied to allow of measurements being made at different positions along the bore.

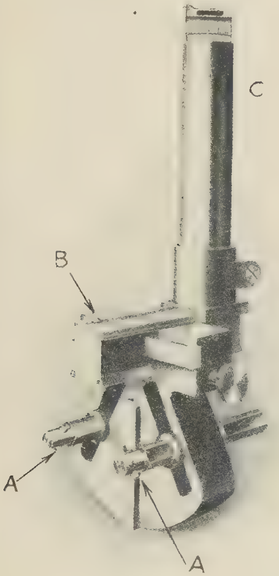


Fig. 203.

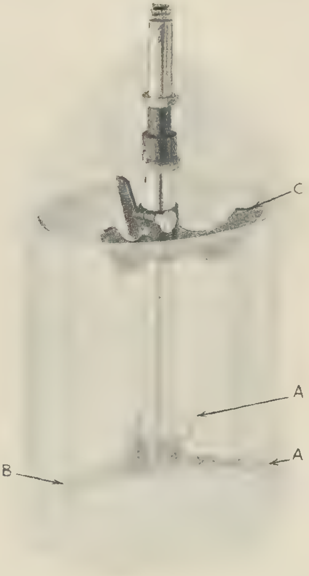


Fig. 204.

Any one head can be made to cover an appreciable range of diameters by means of the screw adjustment on the three contacts, and, by using a series of heads, a total range of diameters from about 3 to 20 inches can be dealt with.

The degree of accuracy which can be obtained by the use of the above comparators depends, for the most part, upon the sensitivity of the minimeter tube used. This may vary from 0·001 to 0·0001 inch, or 0·01 to 0·001 mm., per division, according to the type of tube. As the scale of the indicator is limited to about twenty divisions, the instruments with higher sensitivities can only be used at the expense of correspondingly limited ranges of measurements.

(ii) **Zeiss "Passimeter."**

This is another type of instrument for comparing internal diameters. It is made in a variety of sizes to cover holes ranging from $\frac{7}{16}$ up to 4 or 5 inches in diameter. The internal arrangement of the instrument is shown in Fig. 205.

The indicator head A, containing a system of magnifying levers and gears terminating in a pointer which records against a scale, is attached to a tube B, through which passes a lever C, pivoted at D. One end of this lever is in contact with the indicating mechanism, whilst the other end, fitted with a steel ball, is controlled by a plunger E which can slide in a fitting attached to the end of the tube B. This fitting has screwed to it a plate F, the end view being as shown in the left-hand diagram. The edge of this plate is ground spherically to a slightly smaller radius than that of the hole to be dealt with, and, as the part opposite the plunger E is cut away, contact with a hole takes place at the two corners G, about 120° apart, and at the spherical end of the plunger. The latter is pressed outwards by a spring at its rear end, whilst others at the extremities of the lever C maintain a steady contact between the moving plunger and the ball end of the lever. When inserting the measuring foot into a hole, the plunger can be held back by depressing the stud H. On releasing this, the plunger moves outwards, and the departure of the hole from its nominal size is indicated on the scale. A ring gauge of known diameter has to be employed for setting up purposes.

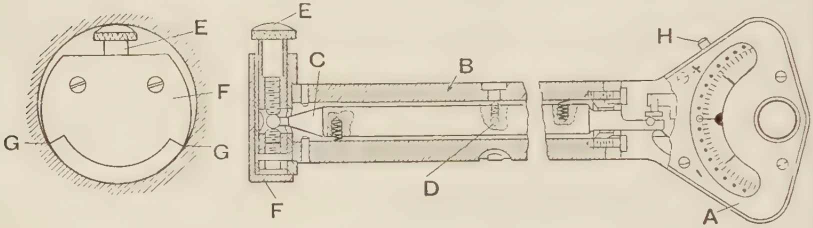


Fig. 205.

The scale is openly divided into thousandths of an inch, and has a range of 0·008 inch on each side of a central zero. The distance between the graduations is about 0·2 inch.

In addition to the indicating pointer, there are two others, the positions of which can be set to indicate the limits from nominal size to which it is desired to work in any particular case.

Any one instrument is made to cover a certain range of measurements by the provision of a number of different end-plates F.

(iii) "**Subito**" **Cylinder Gauge.**

A type of indicator gauge particularly adapted for the measurement of the bores of automobile and other engine cylinders is that made by Messrs. Hahn and Kolb of Stuttgart, and illustrated in Fig. 206. It consists of a tube A carrying at its upper end a dial gauge graduated to read to 0·01 mm., and at the other a cross-piece. The latter is fitted with a ball-ended distance piece B at one extremity and a spring-controlled plunger C at the other. Endwise motion of the latter is transmitted to the dial by a quadrantal-shaped rod D, working in a corresponding hole, and a strut E

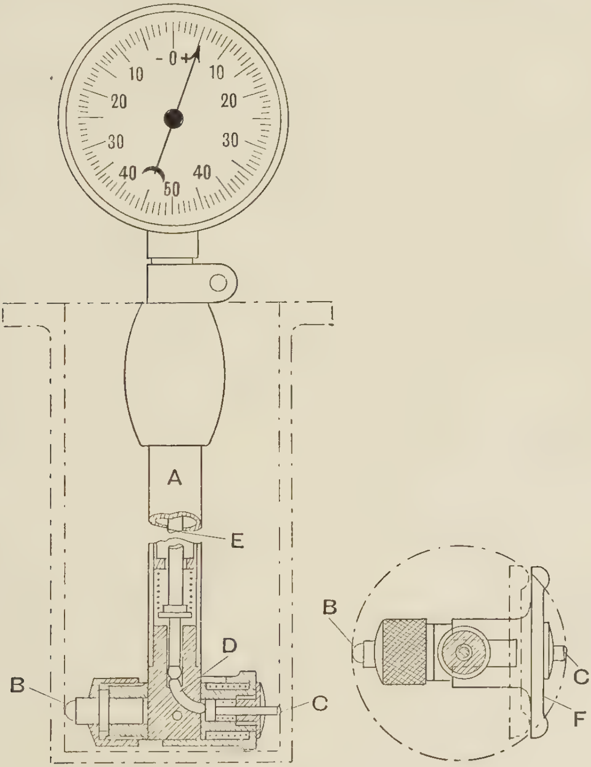


FIG. 206.

which passes through the stem of the instrument. Backlash is eliminated by the action of a spring which keeps the various rods in steady contact.

In order to locate the contacts in a diametral plane in the hole to be measured, the cross-piece has a T-shaped sleeve F, the curved ends of which are pressed against the surface of the hole by the spring shown. When gauging a hole, however, it is still necessary to rock the instrument slightly from side to side and to note the minimum reading on the dial. It should be noted that the indication of the gauge is of a diametral nature, the feet on the sleeve F serving only to assist in locating the gauge in the hole.

The actual range of the measuring plunger C is of the order of one or two millimetres in the smallest size of instrument. This particular size, however, is made to cover a range of from 20 to 35 mm. by the provision of a series of eight distance pieces, B, of graded lengths.

The instrument is made in a variety of sizes, the largest being capable of gauging holes up to 29½ inches diameter.

It is to be understood that this type of gauge serves only as a comparator, initial readings having to be taken with the contacts inserted in some form of internal standard gauge or between the jaws of a micrometer.

(iv) Zeiss Internal Comparator.

An interesting type of comparator for internal measurements, made by Messrs. Carl Zeiss, is shown in Fig. 207. The gauge to be measured is placed upon a table between two brackets, one of which holds the indicator A, in the form of an "Optimeter",* and the other an adjustable anvil B. Two stirrups C, supported pendulum-fashion from brackets D, transfer the contacts with the gauge to the faces of the indicator and anvil.

The upper part of the table supporting the gauge is free to move in the direction of measurement; it can also be traversed from front to back so as to obtain the maximum dimension in the case of ring gauges. In addition, the whole table can be raised or lowered by the hand-wheel shown, so that measurements can be taken at different positions through a ring or across the face of a gap gauge.

The instrument is set up on a standard ring or gap gauge, but, if desired, a standard end gauge can be used for this purpose. In the latter case, the inner ends of the contacts are used and

---

* For description and other uses of this indicator, see Vol. I. p. 333.

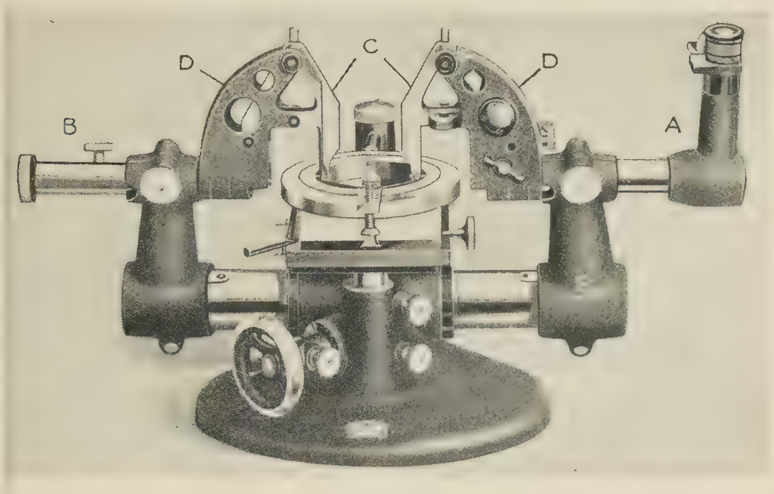


FIG. 207.

allowance has to be made for the sum of the lengths of the two short contact rods.

Note on Three-point Internal Measurement.

It is of interest to note that, unless special precautions are taken, internal gauges having three feet, only one of which is movable, do not record true differences in diameter. Consider the case of a gauge with three contacts, A, B and C (Fig. 208, I), B and C being rigid, whilst A is in the form of a plunger. The movement of the plunger when the gauge is transferred from a hole of radius R_1 to another of radius R_2 is AA′. This, however, exceeds the difference between the diameters of the holes by the amount DE, which depends upon the distance $2a$ separating the contacts B and C.

Taking a general case, the distance H (Fig. 208, II) between the plunger A and the line of the other two contacts B and C is given by

$$H = R + \sqrt{R^2 - a^2}.$$

Differentiating with respect to R,

$$\frac{dH}{dR} = 1 + \frac{R}{\sqrt{R^2 - a^2}},$$

$$\therefore \delta H = \left(1 + \frac{R}{\sqrt{R^2 - a^2}}\right)\delta R = \tfrac{1}{2}\left(1 + \frac{R}{\sqrt{R^2 - a^2}}\right)\delta D,$$

where δD is the required difference in diameter.

For a given value of the ratio a/R, we may write

$$\delta H = K \cdot \delta D,$$

K being a constant, somewhat greater than unity.

Hence, an instrument in which the range is limited and the distance BC is fixed can be made to give satisfactory readings of difference by suitably adjusting the magnification of the indicator or appliance used for measuring the movement of the plunger. Take, for example, an instrument in which R and a are 2 and $1\frac{1}{2}$ inches respectively, we then have

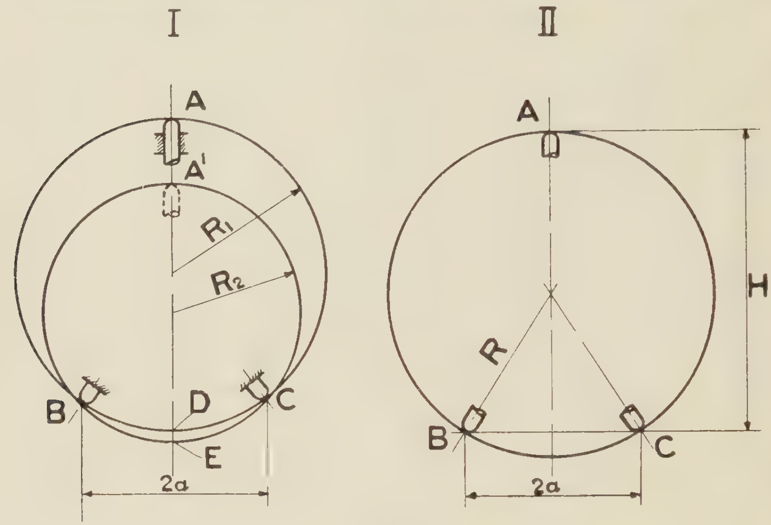


FIG. 208.

$$\delta H = 1{\cdot}256\,\delta D.$$

If each division on the indicator is intended to represent a difference in diameter of 0·0001 inch, the magnification must be adjusted so that the divisions correspond to an actual movement of the plunger of between 0·00012 and 0·00013 inch.

If the instrument is so designed that its range can be extended by lengthening *each* of the contact arms in a radial direction, then it is possible to maintain the ratio a/R constant throughout the settings, and the instrument will be universally correct if its magnification is suitably adjusted for one position of its contacts.

On the other hand, designs are to be found in which the range is altered by moving only the contacts B and C, with the result that the ratio a/R differs appreciably at the maximum and minimum settings. In a particular instrument tested some years ago by the writer, the value of K varied from 1·256 to 1·141. The indicator recorded actual movements of the plunger, so that its readings were erroneous, so far as diametral differences were concerned, by about +26 per cent at one extremity of its range and +14 per cent at the other. Had it been set to suit the approximate mean factor, 1·2, its maximum errors would have been reduced to about ±5 per cent.

(For Additional References, see end of Chapter IX.)

CHAPTER IX

INTERNAL MEASUREMENTS (*continued*)

The Use of Measuring Machines for Internal Measurements

Société Genevoise Machine.

The end-measuring machine made by the Société Genevoise * can readily be adapted for internal measurements by the addition of a pair of U-shaped fittings, A (Fig. 209), to the measuring faces. These fittings are held in place by clamp rings B, and are provided with rounded contacts over which the piece to be measured is placed. The thickness of the ends of the adaptors is such that it is only possible to deal with internal measurements above an inch.

Light articles, such as the gap gauge shown, can be held in position by hand, using, of course, a suitable clip to prevent thermal expansion. Larger pieces can be placed upon a special support which is slotted so as to clear the adaptors. The upper platform of the support is mounted on balls resting in vee-grooves, so that it is quite free to move over a limited range in the line of measurement.

Normally, for external measurements, the indicating plunger of the micrometer headstock is thrust outwards by means of a compression spring, but when arranged for internal work the spring has to be put in tension. This change is readily made by rotating the collar D. Settings are made in the same manner for both forms of measurements by rotating the micrometer wheel until the indicating needle E is brought to the central mark.

The internal measurements have to be carried out with reference to a standard internal gauge. Such a standard having a definite size can readily be built up in the form of a gap gauge by wringing a pair of jaws on to a combination of block gauges.

The size of the gap should approximate closely to that of the gap or diameter to be measured. Only a short range of the micrometer screw is then used in the comparison, and any inaccuracies which may arise from progressive errors in the screw are thus reduced to a minimum.

---

* For description of this machine, see Vol. I. p. 302.

It is hardly necessary to add that, when taking a setting on a gap gauge or ring, care has to be used to obtain either a normal or truly diametral measurement, as the case may be. This presents no difficulty if the behaviour of the indicator is observed as the gauge is moved slightly in various directions. An example of a measurement made in this type of machine is given in Appendix II.

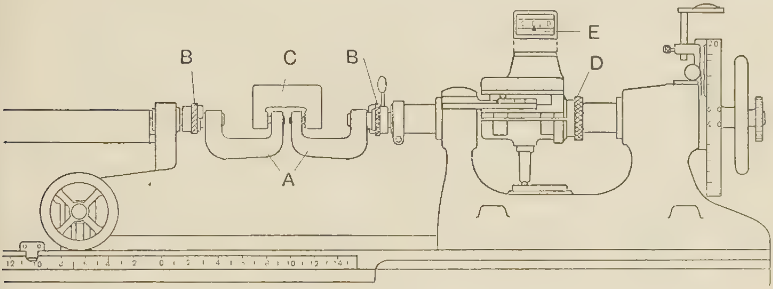


FIG. 209.

The Wickman Machine.

Another type of measuring machine which has provision for dealing with internal measurements is the Universal Measuring Machine by A. Wickman.* A purely diagrammatic arrangement of this machine, as set up for measuring a ring gauge, is shown in Fig. 210. The gauge is clamped to a vertical slide forming part of a massive carriage. This is mounted on balls and is capable of motion in the direction of the arrows, under the control of a micrometer headstock. Contact with the gauge is made with a ball-ended feeler, mounted at the end of a lever which forms part of an optical indicator.

With the assistance of the indicator, the height of the ring is adjusted so as to bring the feeler point on the horizontal diameter. The carriage is then moved so as to transfer the contact of the feeler from one side of the ring to the other, the traverse being measured by means of the micrometer screw and an end gauge of suitable length. In each position the micrometer is adjusted so as to bring the indicator to its fiducial mark. The size of the ring is then obtained by adding the diameter of the feeler point to the measured traverse of the carriage.

---

* For description of this machine, see Vol. I. p. 285.

To carry out such a measurement it is clearly necessary to give the indicator a slight bias, first to one side and then to the other.

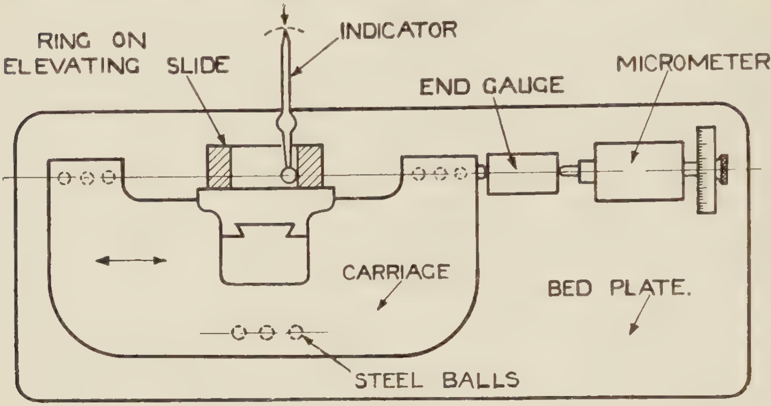


FIG. 210.

Any elastic springing of the indicator, or backlash between its parts, will therefore affect the accuracy of the measurements. Since, in the latest design of the indicator, all pivots are replaced by "crossed-strip" suspensions (see p. 281), there should be little risk of error arising from the latter cause.

N.P.L. "Chord Contact" Machine.

A simple and rather novel scheme for internal measurements of ring gauges, both cylindrical and screwed, is that devised by G. A. Tomlinson at the National Physical Laboratory in 1921. The underlying principle is shown in Fig. 211. A rod A having a steel ball at each end fits loosely in the ring, and its lateral play h is measured. The diameter of the ring can then be obtained from the formula

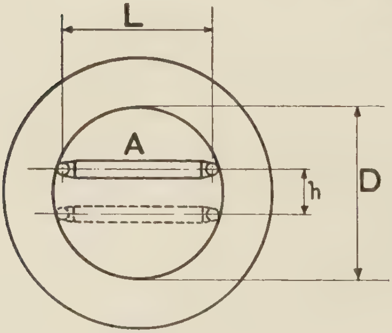


FIG. 211.

$$h^2 = (D - d)^2 - L^2, \quad . \quad (1)$$

where D is the diameter of the ring, d the mean diameter of the balls and L the distance separating the centres of the latter.

If the nominal size of the ring is known, then, for a given rod, it is possible to calculate the theoretical value of the displacement h for a perfect ring. Any error in the diameter of the ring under test will then be detected if the measured and theoretical values of h do not agree.

Moreover, it should be noted that any error in the diameter of the ring becomes magnified in the measurement of h, the degree of magnification depending upon the length of the rod in relation to the diameter of the ring. In practice it has been found convenient to choose the length of the rod for any particular size of ring, so that the diameter errors are magnified five times. That is to say, if the diameter of the ring were 0·001 inch greater than its nominal size, then the rod could be displaced 0·005 inch more than its calculated movement.

The magnification is expressed by

$$\frac{dh}{d\mathrm{D}} = \frac{\mathrm{D}-d}{h} = 5 \text{ (say)},$$

$$\therefore h = \frac{\mathrm{D}-d}{5}, \quad . \quad . \quad . \quad . \quad (2)$$

Then from equation (1),

$$\mathrm{L}^2 = (\mathrm{D}-d)^2 - h^2 = \tfrac{24}{25}(\mathrm{D}-d)^2,$$

$$\therefore \mathrm{L} = \tfrac{1}{5}\sqrt{24}(\mathrm{D}-d). \quad . \quad . \quad . \quad (3)$$

Given D and d, it is possible from (2) and (3) to calculate the required length of the rod and the theoretical value of h. If, on measurement, an error δh be found in h, then the error in the diameter of the ring from its nominal size is $\frac{1}{5}\,\delta h$.

The accuracy to which it is possible to determine the error in the diameter of a plain ring depends not only upon the accuracy of the determination of h, but also upon the measurement of the length of the rod L and the mean diameter of the balls d. These three quantities can each be obtained to an accuracy of about ±0·00002 inch, so that the determination of the absolute value of the error of the ring should be known to within ±0·00005 inch. Comparative values of the errors in different parts of the same ring can be obtained true to within ±0·00001 inch.

The method used for measuring the vertical distance h is illustrated in Fig. 212. The ball-ended rod A is carried horizontally at one end of the five-to-one lever B, which is pivoted on two transverse ball-feet C spaced $1\frac{1}{8}$ inch apart. These feet rest on the upper polished surface of a pile of slip gauges D, the height of which can readily be adjusted by building up on a surface plate below. The balance of the lever is adjusted by the jockey weight W. The height of the gauges D is first chosen so as to bring the lever approximately horizontal, when the rod is resting in its lower position under the action of the throw-over weight F. A reading is then taken with the fixed micrometer head M by sighting the contact on a thin, curved sector E, which is attached to the end of the longer arm of the lever. Under favourable lighting conditions the micrometer can be set to 0·0001 inch. The pile of gauges is then increased by the calculated value of h, and the rod is brought into gentle contact with the upper part of the ring by changing over the weight F. A second micrometer reading is then taken. The measured error in h for the particular ring is equal to one-fifth of the difference between the calculated value of h and the displacement of the sector E. as measured by the micrometer, with the appropriate sign. Since the error in the diameter is again one-fifth of δh, it will be seen that diametral errors are magnified 25 times at the micrometer.

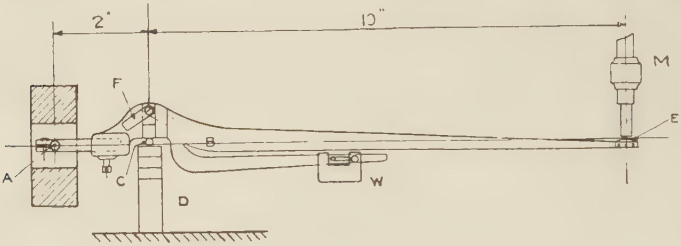


Fig. 212.

When measuring a plain ring, the ball-ended rod is set by eye square to the axis of the ring. Any small error in this adjustment produces only a cosine error in the final result and can be neglected.

It is found convenient to use adjustable ball-ended rods made in two parts and fixed in a suitable holder, as shown in Fig. 213. The gap between the two parts is set by means of slip gauges to give the required centre distance between the balls. To facilitate this setting, the inner end of one rod is made plane and the other spherical. The ball-ends consist of hardened steel balls, which should be specially selected and accurately measured. They are fixed to the rods with hard solder.

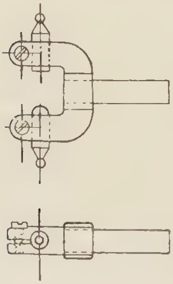


Fig. 213.

A general view of the machine is shown in Fig. 214.

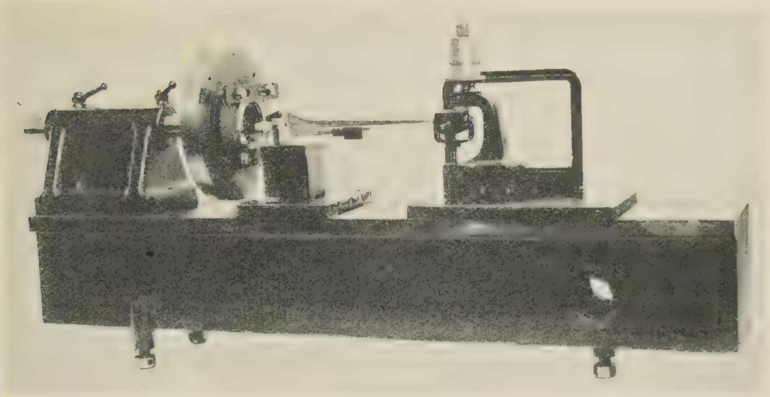


Fig. 214.

N.P.L. Internal Measuring Machine—Displacement Type.

A second type of internal measuring machine has been designed and constructed at the National Physical Laboratory, the general scheme of the machine in this instance being due to E. M. Eden.

The machine was primarily intended for measuring the effective diameter of ring screw gauges, using, as a basis, the diameter of a vee-groove cut in the surface of a plug—the advantage being that such a vee-groove can be standardized much more accurately than one cut internally. In a similar manner, the diameter of a cylindrical ring can be compared with that of a standardized plug gauge.

The important features of the machine are shown in Fig. 215, the lower part of which is a plan view and the upper a sectional elevation from one side. Essentially, the machine consists of a carriage C, which can travel freely in the direction XY; and a sensitive indicator D, provided with a double spherical-ended stylus. The position of the carriage, to which the standard plug or ring gauge is clamped with its axis horizontal, can be measured at each end of its travel by micrometer headstocks E and F. In making a comparison, four readings of the position of the carriage are taken. The first pair, I and II, Fig. 216, are made with the ends of the stylus brought into contact, in turn, with each side of the standard plug, and the second pair, III and IV, when contact is made on the sides of the ring gauge.

If x and y denote the movements of the carriage between positions I and IV and between positions II and III respectively, and S is the diameter of the standard plug, then the diameter D of the ring is given by

$$D = x + y - S.$$

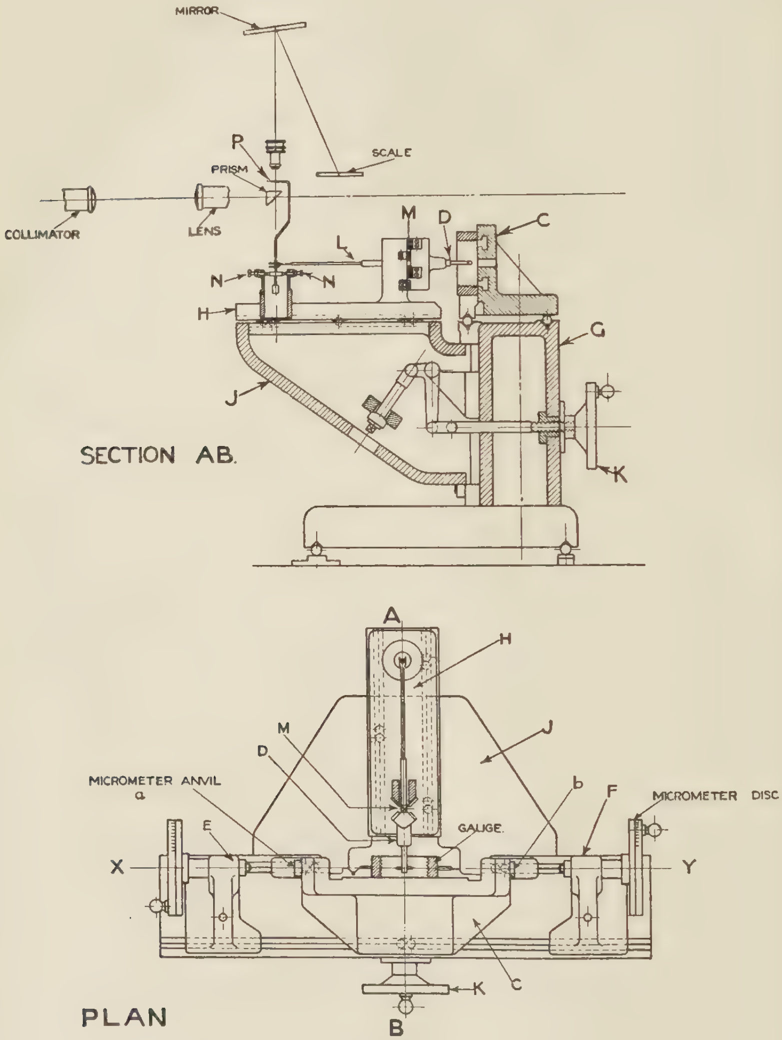


Fig. 215.

It will be noted that this measurement is independent of the length of the stylus or the exact sphericity of its ends. A little consideration will show that it is also uninfluenced by any flexibility of the stylus arm, or backlash of the indicator to which the stylus is attached.

The carriage C is mounted on balls located in vee-grooves in the front part of the bed G (Fig. 215), and can be made to bear against either micrometer at will by means of a throw-over weight. An oil dashpot is provided to prevent any violent contact between the carriage and the micrometer faces. The same movement causes the pressure of the indicator to be transferred from one side to the other, so that when the carriage is to the right the indicator has a bias towards the left, and vice versa.

The displacements x and y of the carriage are not measured wholly with the micrometer screws. In each case, the bulk of the movement is taken up by block gauges wrung, in turn, on to the two anvil faces a and b of the carriage. Only the last twentieth of an inch or so is left for the micrometer screws.

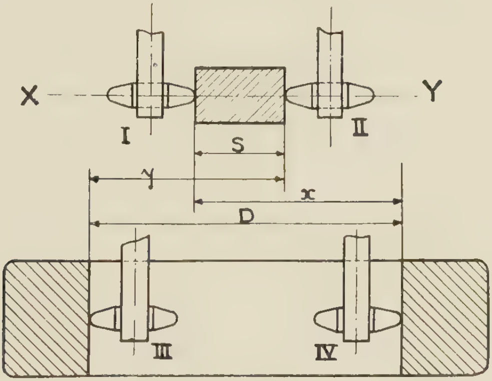


FIG. 216.

The indicator is on a second carriage, which is free to move on balls in the direction AB. This enables measurements to be made at different depths in the ring. The carriage is supported on a bracket J, which can be moved up and down a vertical slide at the rear of the main casting G. Its motion is controlled by a hand-wheel K and a system of levers, so designed that the pull on the bracket tends to hold it firmly in contact with the slide. This vertical adjustment in the height of the indicator is required in order to obtain correct diametral settings on the standard and the gauge.

The indicator itself consists of a compound lever, the first arm L, which carries the stylus at its outer end, being supported on two pairs of flexible steel strips, so that it is capable of a limited motion about a vertical axis at M. The rear end of this arm is forked and engages with a second lever, pivoted at NN and carrying a cross-hair at its upper end P. A movement of the stylus in the direction XY thus causes a deflection of the cross-hair in a parallel direction. This deflection is further magnified optically by the arrangement shown, so that motions of the stylus are finally observed, to a magnification of approximately 1000 times, on the scale placed just above the machine.

In taking a reading on either the standard or the gauge to be measured, the throw-over weight is set to one side and the appropriate micrometer rotated until the adjacent end of the stylus makes contact, and brings the image of the cross-hair into view on the scale. The whole indicator is then raised, or lowered, by the hand-wheel K so as to determine the position which gives the maximum deflection, after which the micrometer is finally adjusted to bring the cross-hair to the fiducial mark. The throw-over weight is then reversed, and a similar setting made on the other side of the gauge.

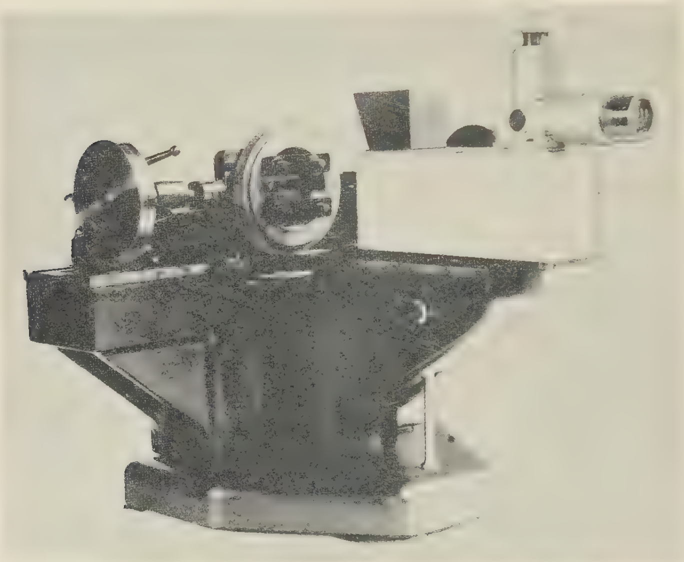


Fig. 217.

This machine was originally intended to give measurements accurate to 0·0001 inch. Experience has shown, however, that with care it can be depended upon to an accuracy of one or two hundred-thousandths of an inch, especially if the comparison is made more directly by the use of a standard in the form of a gap gauge, built up from block gauges.

The machine has a capacity of about 4 inches. A general view of it is given in Fig. 217.

An example of measurements made in the two N.P.L. types of machines is given in Appendix II. p. 338.

The two N.P.L. types of machines just described can also be used for internal measurements of screwed ring gauges. Their application to this purpose will be dealt with in a later volume under the heading of screw ring measurements.

ADDITIONAL REFERENCES FOR CHAPTERS VIII AND IX

Wickman Universal Measuring Machine, Booklet on "Accurate Measurement" issued by Messrs. Alfred Herbert Limited.

"Machine for the Measurement of Internal Diameters," G. A. Tomlinson, *Engineering*, vol. 112, p. 558 (1921).

"Zeiss Internal Measuring Machines," A. Steinle, *Maschinenbau*, p. 244 (1923–1924); H. Kessder, *Präzision*, vol. 2, p. 191 (1923).

Test Comparators, Booklet No. 239 issued by La Société Genevoise.

"Arrangement of Minimeter for Internal Measurements," N. Pfleiderer, *Präzision*, vol. 2, p. 213 (1923).

"Bath Internal Micrometer," *Amer. Mach.*, vol. 54, pp. 578, 1102 (1921).

"Taft-Peirce Micrometer Plug Gauge," *Amer. Mach.*, vol. 59, p. 747 (1923).

"A Special Internal Gauge," E. A. Suverkrop, *Amer. Mach.*, vol. 48, p. 649 (1918).

"Adjustable Internal Gauge," Lawrence, *Amer. Mach.*, vol. 45, p. 119 (1916).

"Measurements of Internal Diameters," H. T. Wright, *Machinery*, vol. 27, p. 213 (1925).

"Arrangement for Measuring Small Holes," *Präzision*, vol. 2, p. 134 (1923).

"Gauging the Bore of 4·7-inch Gun," E. A. Suverkrop, *Amer. Mach.*, vol. 48, p. 649 (1918).

"Inspection Gauge for Cylinder Bores," *Machinery*, vol. 21, p. 212 (1922).

"Inside Indicator Gauge" (C. E. Johansson), *Machinery*, vol. 33, p. 115 (1928).

"'Pressfinish' Method for Enlarging and Polishing Holes," *Amer. Mach.*, vol. 69, p. 989 (1929).

CHAPTER X

TESTS FOR FLATNESS AND STRAIGHTNESS

In ordinary workshop practice, the production of flat surfaces resolves itself into a copying process, and the degree of perfection obtained in any particular case depends to a large extent upon the truth of the guiding surfaces of the machine tool used. These surfaces, in turn, are derived from others whose accuracy is finally based upon that of a master surface, which itself has to be produced by a process of generation.

Whitworth was the first to realize that accuracy in engineering production, and the means of controlling it by gauges and measuring appliances, are based upon the generation of truly plane surfaces. His pioneer work in that direction, some fifty years or more ago, laid the foundations of modern methods of interchangeable manufacture. It is also of interest to note that the advances made during the last decade in the production of gauges and measuring instruments of extremely high precision have been brought about largely by a reversion to some of the fundamental principles which he established.

Generating Flat Surfaces.

The system of originating a flat surface, as practised by Whitworth, is to work three metal plates together systematically in pairs until the surface of each is a counterpart of the other two. This fitting together of the plates can be brought about automatically by rubbing one plate over another with suitable abrasive between their surfaces. Continual rubbing causes the regions of contact to spread more and more over the surfaces, until, under good conditions, fitting takes place over the whole surface of each plate. The introduction of a third plate is necessary, since the interaction of the plates of a single pair only might easily develop concave and convex surfaces of equal radii. By systematically working three plates together, any tendency in that direction is prevented.

Instead of allowing the plates to rub each other down, the metal can be removed at the prominent regions by judicious filing or scraping. The plates are still rubbed together in pairs, but only to such an extent as to throw the high regions into relief, a process which is facilitated by lightly colouring the surface of one plate with a very thin film of some suitable pigment, such as Prussian-blue, or rouge in oil. This method of hand-finishing, however well done, necessarily produces a patchy surface consisting of a number of small elevated areas separated by depressions. The more time spent in finishing the plates, the greater will become the tendency towards a continuous surface. The expenditure of considerable time and patience, however, is required to produce an effective surface greater than 50 per cent of the whole. Nevertheless, this broken type of surface is sometimes preferable to the continuous surface produced by lapping the plates together, for there is less tendency for wringing to occur when two scraped surfaces are brought into contact, or when they are applied to other surfaces which it is required to test. On the other hand, a plate with a scraped surface is clearly more liable to deteriorate in use through local wear.

Types of Surface Plates.

(i) *General Designs.*—A typical design of surface plate is shown in Fig. 218. This illustrates a set of hand-finished, cast-iron plates

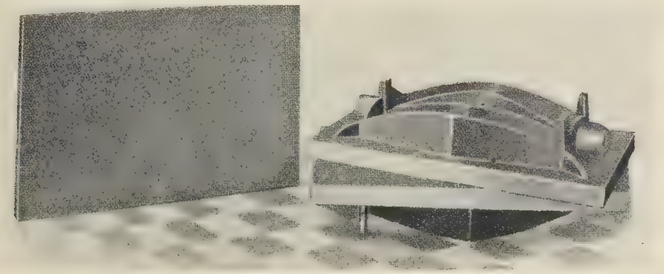


FIG. 218.

as made by the Newall Engineering Company. Such plates are produced in a wide range of sizes from about three inches square up to large marking-off tables with dimensions of ten feet or more.

When required for testing the surfaces of machine beds, the plates usually take an elongated form as in Fig. 219, the width of the surface varying from about $1\frac{1}{2}$ to 3 inches according to the length. Such plates are generally made bow-shaped for stiffness, and the supporting feet are placed in the neighbourhood of the "Airy points."

(ii) *Ageing as a Preventive of Warping.*—Surface plates are almost invariably made of cast-iron, which should be quite sound and close-grained. Owing to the internal strains set up during the casting process, cast-iron has a tendency to warp with age. It is usual, therefore, when manufacturing surface plates, to allow the castings to season for a year or two after rough machining before any attempt is made to finish the surfaces. Subjection to mechanical vibration and variation of temperature are found to assist in relieving the initial strains. A treatment which is said to be quite successful in artificially ageing cast-iron is to anneal it in the neighbourhood of 700° C. for about two hours and then allow it to cool down slowly. Such a treatment obviates any undue delays in manufacture.

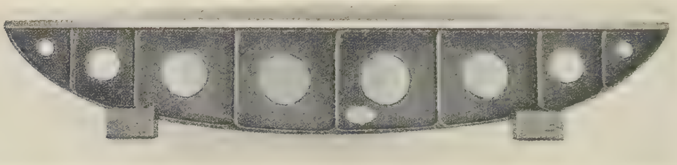


Fig. 219.

(iii) *Special Design of Rotatable Surface Plate.*—A type of surface plate which is particularly useful for accurate work in conjunction with block gauges is that shown in Fig. 220. It consists of a 7½-inch diameter hardened steel plate, lapped to a mirror-like finish and flat to within 0·00001 inch. The underside of the plate, which is annular, is lapped truly parallel with the top surface, and rests upon a similar lapped surface of a massive cast-iron base provided with levelling screws. A thin film of paraffin between the two surfaces permits the plate to be rotated freely if required, the necessary lateral guidance being given by a loosely-fitting spigot at the centre. This feature is particularly useful in certain tests where it is required to rotate an object truly in one plane.

A small steel pad is screwed to the base, near the periphery of the plate, with its upper surface lapped flush. With the aid of this, it is possible to carry out such a test as that illustrated in the figure. Here, the thicknesses of a number of steel blocks are being compared with a standard block wrung on to the pad. By rotating the plate, each block is brought into position in turn, and the comparison is made with a steel knife-edge—a method which, under suitable conditions, is capable of an accuracy of 0·00001 inch.*

This type of surface plate was designed by A. J. C. Brookes, and is made by the Pitter Gauge and Precision Tool Company.

It may be mentioned that it is not desirable to wring block gauges on to lapped surface plates of cast-iron. As a result of their own finishing process, the surfaces of such plates are invariably charged to some extent with abrasive, and they act, therefore, as laps.

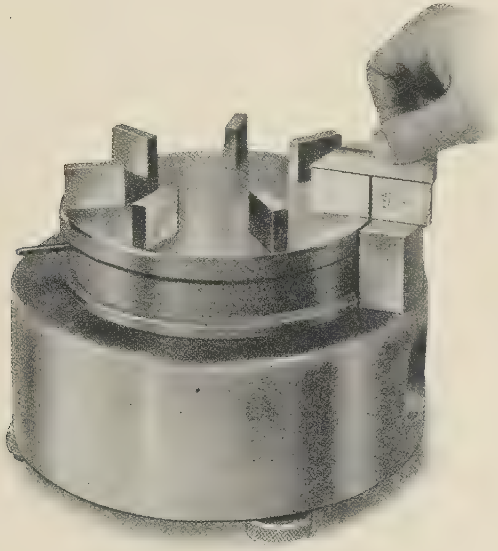


Fig. 220.

(iv) *Rigidity of Surface Plates.*—Reverting to the subject of rigidity and stiffness, in the case of lapping plates, where the highest precision is required in the flatness of the surface, special precautions have to be taken in supporting the plates so as to minimize straining actions which would be likely to affect the truth of the surface. One method of dealing with this problem is shown in Fig. 221, which gives a view of the underside of an 18-inch plate. This plate has nine points of support on the underside, in the form of short vee-grooves, three only of which are visible. These grooves, six of which are towards the edge of the plate and the other three near the centre, are divided into three groups. Each group rests upon three ball-ended feet, fixed near the corners of a triangular plate. Two of these plates are shown in position. The plates are supported in turn, each at a suitable point, upon a single ball contact, so that it can adjust itself to any lack of uniformity in the depth of the vee-grooves. The lapping plate is, therefore, virtually supported on three feet, but the reactions of these supports are distributed over the plate at the nine points mentioned, each of which takes its proper share of the load.

---

* See Vol. I. p. 87.

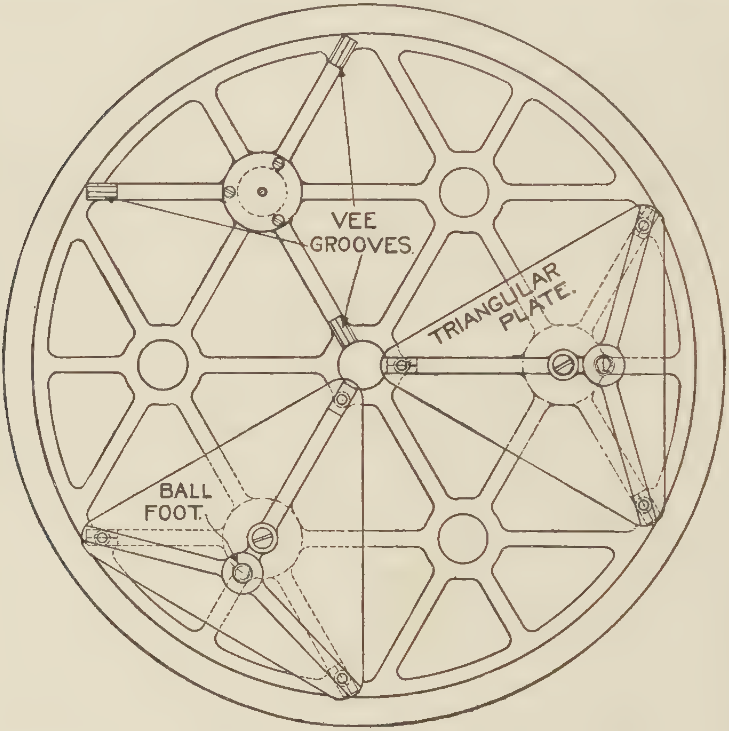


FIG. 221.

This scheme is a simplification of that adopted by Lord Rosse when polishing the six-foot speculum mirror of his large telescope.* He used as many as 81 points of attachment, which, by the above method of successive grouping in threes, were finally reduced to only three supports. Both the mirror and the lapping plate were treated in this manner.

---

* Pollard, *Mechanical Design of Scientific Instruments.* Cantor Lecture before Royal Society of Arts, 1922.

Methods of Testing Flatness.

Before dealing in detail with the various methods for testing flatness and straightness as practised in workshops, test-rooms and laboratories, it may be stated that each resolves itself into a particular method of comparison with a standard. The methods of carrying out the comparison and the types of standards used vary in the different tests, but the principle is the same throughout.

(i) *Comparison with Surface Plate.*—The simplest method of testing the flatness of a surface, and the one usually adopted in the workshop, consists of direct comparison with a surface plate by bringing the two into contact. The comparison is made with the assistance of some suitable marking material on the plate, as previously mentioned. Colouring material becomes transferred to the prominent parts of the surface being tested, and, by noting the distribution of the coloured patches, a general impression can be obtained as to the flatness of the surface.

It sometimes happens that the marking occurs quite locally in only a few positions, indicating that for the most part the surface is low, but it is not readily possible by this form of test to give any statement as to the depths of the depressions present. A fairly close estimate of the errors can be gained, however, by inserting a thin piece of mica, metal-foil or paper of measured thickness between the two surfaces in the region of the depression, and noting the general behaviour of the upper plate when pushed gently from different directions. If the thickness of the packing introduced exceeds the depth of the depression by even only a few ten-thousandths of an inch, there will be a noticeable tendency for the plate to rotate about the position occupied by it. A few experiments of this nature with different thicknesses of packing will give a fairly close idea of the errors present.

(ii) *Use of Optical Flats.*—The method of testing the flatness of a surface by comparison with a second surface of known flatness can be carried to great refinement if the standard surface is of glass in the form of an optical flat or proof plane. When such a glass plate is brought into fairly close contact with the surface to be tested, extremely small errors in flatness of the surface can be detected by noting the configuration of the bands, or fringes, which are formed by optical interference effects in the thin air gap enclosed between the two surfaces.* These fringes are multicoloured when viewed in ordinary white light. A much clearer effect is obtained if the test is carried out in monochromatic light; the fringes then appear black on a uniformly coloured background.

---

* The theory of the formation of these interference fringes is given in Vol. I. Chapter III.

A special outfit designed by Messrs. Adam Hilger, Ltd., for carrying out such optical tests is shown in Fig. 222. It comprises a box, lined with black velvet, containing three optical flats, and having in the lid a coloured, translucent screen which is raised automatically when the lid is lifted. The tests are carried out in the shadow of this screen, which, when placed before a window, or some other source of white light, provides a diffused illumination sufficiently monochromatic to give well-defined interference fringes. Two of the flats are for ordinary use, whilst the third is intended to be reserved as a reference standard, against which the others can be checked periodically by use of the interference phenomenon.

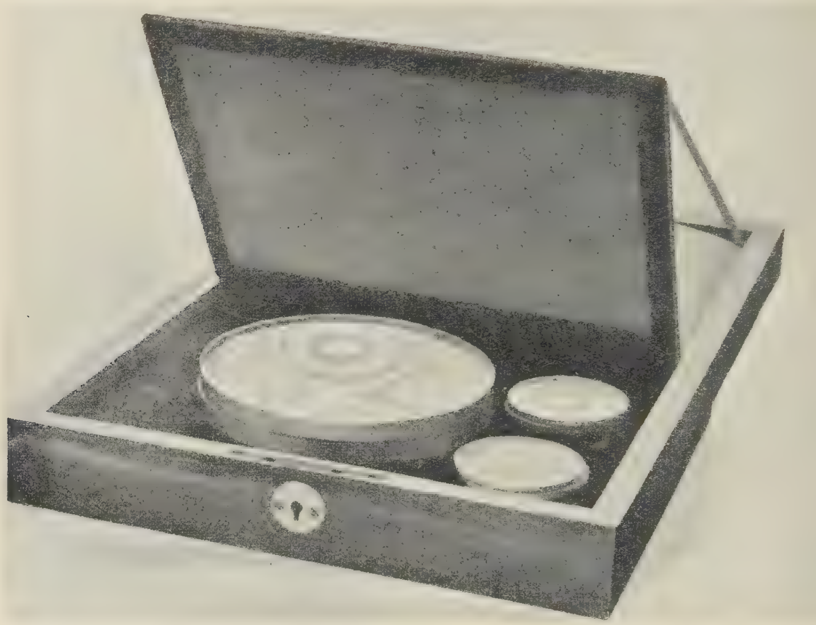


FIG. 222.

Examples illustrating the sensitivity of this method of test are shown in Fig. 223 * (A and B). In the former it will be noted that the fringes are distinctly curved, but comparison with the dotted straight line shows that the deviation from straightness does not exceed the width between adjacent fringes. This indicates that

---

* Reproduced from *The Iron Age* by courtesy of the Editor.

the departure from true flatness is within half a wave-length of the monochromatic light used, *i.e.* the surface is true to within about 0·00001 inch over its whole area. On the other hand, the fringes shown in B are considerably warped, but even in this case the departure from flatness does not exceed about 0·0001 inch.

In applying this form of test, care has to be taken not to allow the optical flat to wring itself on to the surface being tested. The adherence produced by wringing tends to strain the flat, and is likely to give rise to an erroneous impression as to the flatness of the surface.

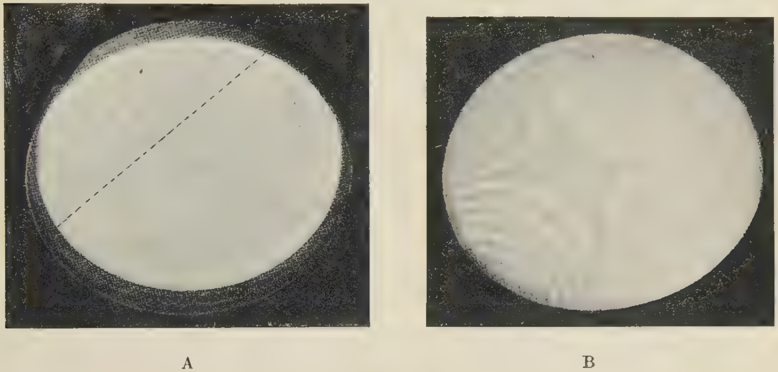


FIG. 223.

It is evident that the sensitivity of this optical test rather limits its scope, confining its use only to those surfaces which are closely flat. The method is particularly applicable to the examination of the faces of end gauges, or hardened steel surfaces not exceeding two or three inches in diameter—the size covered by an ordinary optical flat at one setting. Larger surfaces have to be dealt with in sections, as the cost of large optical flats becomes rather prohibitive.

(iii) *Straight-edges and their Uses.*—The type of straight-edge used in ordinary engineering practice consists of a rectangular steel plate, Fig. 224, about $\frac{1}{16}$ to $\frac{1}{8}$ inch in thickness, with parallel, straight edges. They are generally made with lengths up to about six feet.

FIG. 224.

For refined tests over short lengths the working edge is bevelled off and finished to quite a small radius, so that line contact is obtained with the surface under observation.

Two designs of this "knife-edge" type are shown in Fig. 225. The upper one is the Johansson form, with a triangular section and three working edges; the lower one is the Brown and Sharpe design with a single edge. Hardened steel is used in both cases, and careful lapping of the edges renders them true to one or two hundred-thousandths of an inch. The Johansson type has an ebonite handle to avoid local heating, which would tend to distort the bar and destroy the truth of its edges.

Using straight-edges of these types, departures from flatness of a surface of the order of 0·0001 inch can be readily observed against an illuminated background. Under good conditions of illumination, the light escaping through a gap caused by an error of only 0·00003 inch is still visible. It is interesting to note that a gap narrower than about 0·0001 inch no longer appears white, but tinted, the colour varying with the width. This is due to optical interference. It has also been shown by G. A. Tomlinson, in an investigation at the National Physical Laboratory, that when reduced below 0·000025 inch, all coloration disappears and the gap appears black, due to the same phenomenon.

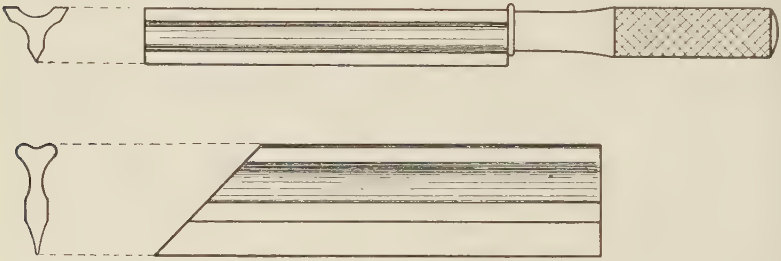


Fig. 225.

It is possible to use a straight-edge below the limit mentioned above for the sighting test, by observing the degree of uniformity of the polished mark left upon the surface under investigation when the knife-edge is gently scraped across it. Errors as small as 0·000005 inch can be detected in this manner.*

Turning now to the use of longer straight-edges of the plate form, Fig. 224, it is desirable at the outset to make some mention of a source of error which is not usually recognized. In carrying out tests

* See Vol. I. p. 87.

some years ago upon a 72-inch steel straight-edge having the usual type of section, 3 inches deep by $\frac{1}{8}$ inch thick, the author was somewhat surprised to find that, when supported on edge at the ends, the centre sagged by as much as 0·0045 inch. Also, on transferring the supports to near the centre, the ends of the bar were found to droop by approximately 0·0025 inch. These deflections, which were substantiated by calculation,* showed rather an unexpected lack of stiffness of long bars of this description. The effect of this lack of rigidity when using the straight-edge for testing a horizontal surface is evident. Whether the test be carried out by the use of "marking", or by inserting a number of packing pieces of equal thickness (such as cigarette papers) between the straight-edge and the surface, no error would be apparent in the surface unless it were either concave by more than about 0·004 inches or cambered by more than 0·002 inch. Moreover, errors which might be present in excess of these figures would be shown at less than their true values.

It is clear from Fig. 226, that this elastic deformation of the straight-edge, which takes place when it is supported either at the ends, as at A, or at the centre, as at B, should be appreciably reduced if the supports are moved to some suitable intermediate position, as at C.

A mathematical investigation of the problem at the National Physical Laboratory by C. H. Grant (details of which are given in Appendix III.) showed that, in order to obtain the minimum amount of distortion, the supports should be separated by a distance equal to 0·554 of the length of the bar. In the case of the 72-inch straight-edge referred to above, the departure from straightness can

---

* The deflections at the centre and the ends are equal to $5/384\,\frac{wL^4}{E\,.\,I}$ and $1/128\frac{wL^4}{E\,.\,I}$ respectively, where L is the length, w the weight per unit length, and I the moment of inertia of the cross-section of the bar about the horizontal axis through its C.G. It will be noted that the deflections vary as the 4th power of L, so that shorter straight-edges which, in addition, usually have the advantage of proportionately deeper sections, deform considerably less than the 72-inch example referred to. The two sizes given below have been taken from the catalogue of a well-known maker, and their deflections have been calculated for the two arrangements of the supports:

Dimensions of Straight-Edge. (Inches.)	Deflections.	
	Supported at Ends. (Inches.)	Supported at Centre. (Inches.)
$36 \times 2\frac{1}{2} \times \frac{7}{64}$	0·0004	0·00025
$39 \times 3\frac{5}{8} \times \frac{1}{8}$	0·00025	0·00015

be reduced to the negligible amount of 0·00009 inch by supporting in this position. If supported at the " Airy points ", *i.e.* with the supports separated by a distance of $\frac{L}{\sqrt{3}}$, the deformation is still quite small, but is about double the figure just mentioned.

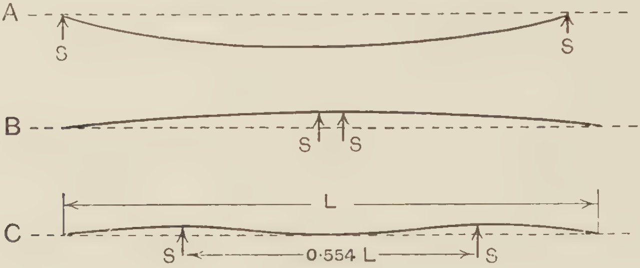


FIG. 226.

In using a straight-edge for testing a surface, cognizance naturally has to be taken of any errors which it may possess, in addition to those introduced on account of elastic deformation. The following method, devised some years ago at the National Physical Laboratory,* enables a parallel-sided straight-edge to be used for testing a surface along a given line, without any previous knowledge as to the errors of the straight-edge itself. The method is analogous to the system of checking three surface plates in pairs.

Three sets of unknown quantities are involved, the errors of the two sides of the straight-edge and those of the surface to be tested. These can be connected by two equations obtained from comparisons between the surface and the two edges in turn, by using the method about to be described. A third equation, which is necessary for a solution of the problem, is derived from the sum of the errors of the two edges. The latter is obtained by taking measurements of the width of the straight-edge at a series of equidistant sections, a_0, a_1, a_2, etc., Fig. 227, throughout its length. At any particular section, let a be the departure of the edge AB from the mean line PQ, and β the corresponding error of the opposite edge CD from its mean line RS. By plotting the measurements of the widths, and drawing a mean straight line through the points, it is possible at every section to obtain the difference, $(a+\beta)$, between the actual width and the width between the average lines PQ and RS. The values of $(a+\beta)$ can then be plotted, as in the curve in the lower part of Fig. 227.

---

* See *Report Nat. Phy. Lab.*, 1914–1915, p. 85.

Turning now to the comparisons between the surface to be tested and the edges AB and CD in turn, the straight-edge is supported off the surface on two unequal block gauges, G_1, G_2, Fig. 228, the sizes of which, for example, may be 0·110 and 0·120 inch, so that a slightly wedge-shaped gap is formed between the surface and the lower edge. The positions of the supporting gauges are made to agree with that which gives the least elastic distortion of the straight-edge (see Fig. 226, C). Block gauges of intermediate sizes, differing consecutively by 0·001 inch, such as 0·111, 0·112, etc., are then inserted in the space between G_1 and G_2 and slid towards the narrow end until they fit the gap. Other gauges are placed similarly on the outsides of the two supporting ones. If both the surface and the edge AB are straight, the taper of the gap will be uniform and all the gauges will be equally spaced. In all probability, however, the presence of errors in the straightness of the edge AB and/or the surface will cause the gauges to deviate from their correct positions with respect to G_1 and G_2. From a measurement of the distance x between a gauge G_3 and its correct position mn, it is a simple matter to determine the error in the width of the gap at mn. This is done for each of the gauges. If γ_1 is the error in straightness of the surface at mn, the error in the gap thus obtained is equal to $(a_1+\gamma_1)$, where a_1 is the error of the edge

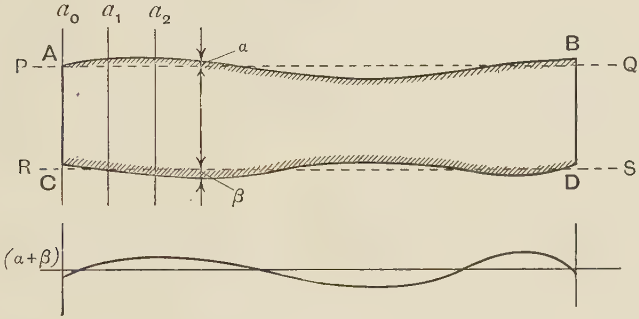


FIG. 227.

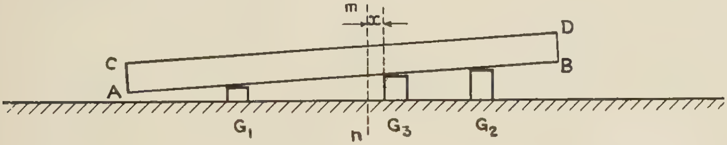


FIG. 228.

AB at the position under consideration. On inverting the straight edge, a corresponding series of values $(\beta+\gamma)$ can be obtained. These two series of errors are plotted in the same manner as those for $(\alpha+\beta)$ in Fig. 227. By taking differences between the three curves in pairs and halving them, three others can be derived which will represent the individual values of α, β and γ over the length of the straight-edge and that of the surface investigated.

The sensitivity of the method of gauging the tapered gaps enables a high accuracy to be obtained when testing a surface by this method.

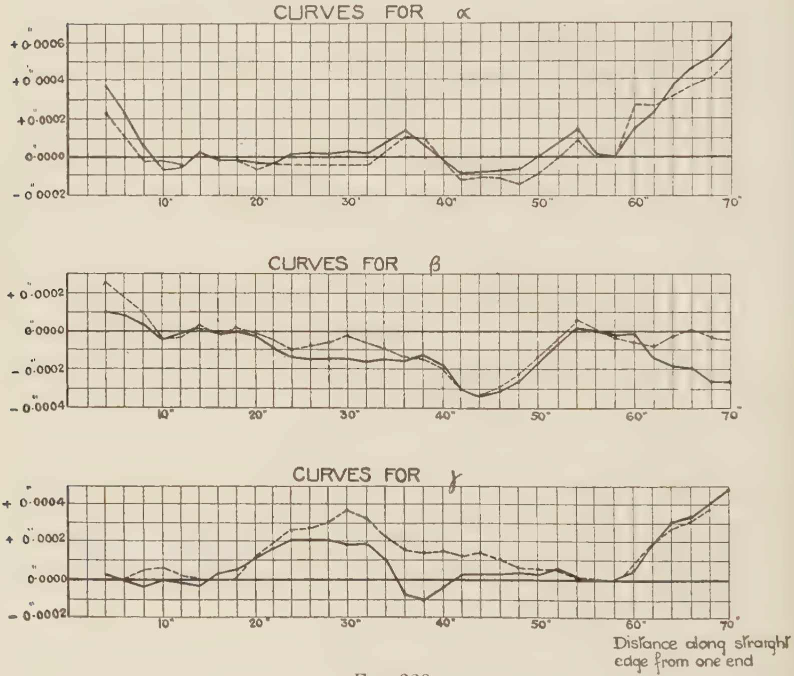


Fig. 229.

It may be of interest to refer to the results obtained at the National Physical Laboratory from an actual test carried out on the bed of a lathe using a 72-inch straight-edge. In order to obtain a check on the results, and to gain some knowledge of the general accuracy of the method, the measurements of the tapered gaps were repeated after turning the straight-edge end for end. Two curves for each of the quantities α, β and γ were thus obtained. These are shown in Fig. 229, from which it will be seen that in each case the general agreement between the two determinations is of the order of 0·0001 inch. It is also of interest to note from the curves for α and β that the errors in straightness of the two edges of the straight-edge used are within approximately 0·0005 inch. There is a general similarity between the contours of these edges, due, probably, to their having been finished on the same grinding machine.

Use of Sensitive Levels for Testing Straightness.

The constancy of the direction of the force of gravity in a locality can be used as a basis for testing the flatness of a surface. The comparator used takes the form of a level tube, which should have a radius of curvature of 100 feet or more, according to the accuracy required in the test.*

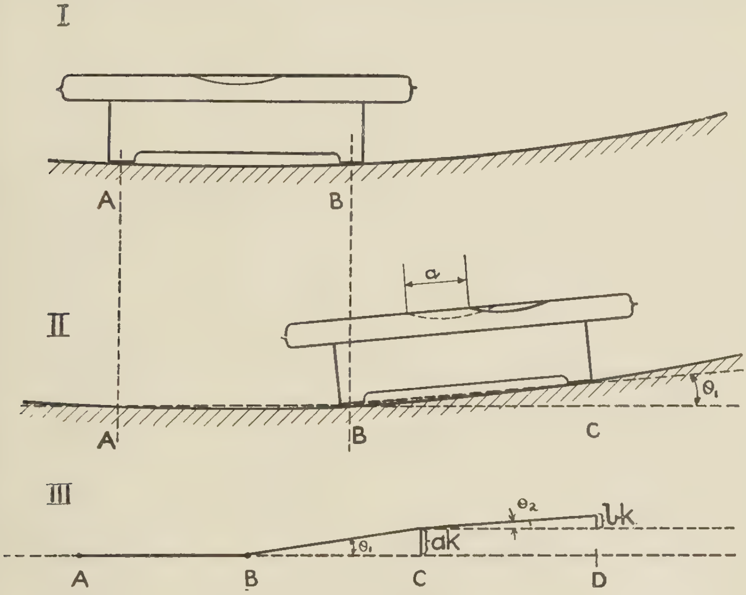


Fig. 230.

The level tube is mounted on a suitable base, the underside of which is relieved over the middle portion, as shown in Fig. 230, I. Having placed the level at one end of the surface to be tested and noted the position of the bubble against its scale, the base is moved along the surface in the direction in which the test is required, until the left foot occupies the position B, as at II, when the reading of the bubble is again recorded. The base is moved on step by step in a straight line until the whole length of the surface has been covered. By correlating results thus obtained along a number of lines, the contour of the surface can be obtained.

---

* The ordinary workshop level usually has a radius of only about 20 feet, and is not sufficiently sensitive for the purpose in view. Suitable ground level tubes with radii up to 800 feet can be obtained from Messrs. Cooke, Troughton and Simms, York, or Messrs E. R. Watts, London.

The calculation of the results is a simple matter. First of all, it is necessary to know the value of a scale division on the level in terms of angular tilt. This can be determined by tilting the base through a series of known angles by means of block gauges under the feet.* Let the value of one division correspond to a tilt K over the base length AB. If the deflections of the bubble in positions BC and CD (see diagram III) are a and b respectively, the corresponding tilts will be aK and bK. The deviation of the surface from the datum line AB is then obtained by integrating the various tilts. At D, for example, the deviation is $(a+b)$K.

The sensitivity of any given level tube can be increased for purposes of this test by shortening the base length AB. It is not desirable, however, to use too short a base, as it naturally involves a correspondingly large number of readings to cover a given surface. With a tube having a radius of 200 feet, a convenient base length is 2·4 inches, since one scale division, which usually measures 0·1 inch, then corresponds to a tilt of 0·0001 inch over the base length.

An interesting development of this method has been made by A. J. Hockaday at the National Physical Laboratory, in which use is made of the measuring head of a level comparator † arranged on a traversing support. The sensitivity has been increased to such an extent that it is possible to detect errors in flatness of the order of 0·000005 inch in a surface plate about a foot in diameter. ‡

A level can also be used for investigating " wind " or twist in machine beds. For this purpose it is placed transversely to the general direction of the bed, and any deflections of the bubble noted as the level is moved from one end of the bed to the other.

Motions of carriages and slides, such as the saddle of a lathe or the table of a planing machine, can be readily checked in the vertical plane by mounting a sensitive level upon them.

A type of workshop level suitable for such tests is shown in Fig. 231. The brass tube which encloses the level tube is mounted in a length of channel iron, the base of which is ground flat. The level is set true with the base by means of the usual screw adjustment, as shown. For general purposes a level tube of about 200 feet radius gives sufficient accuracy.

---

* See also p. 137.

† See Vol. I. p. 249.

‡ See *Report of the Nat. Phy. Lab.*, 1926, pp. 150-152.

By lapping the base of the channel, and wringing on a pair of equal block gauges to act as feet, this type of mounted level can be used for testing surfaces by the method described above. The sensitivity can be readily adjusted by suitably spacing the block gauges.

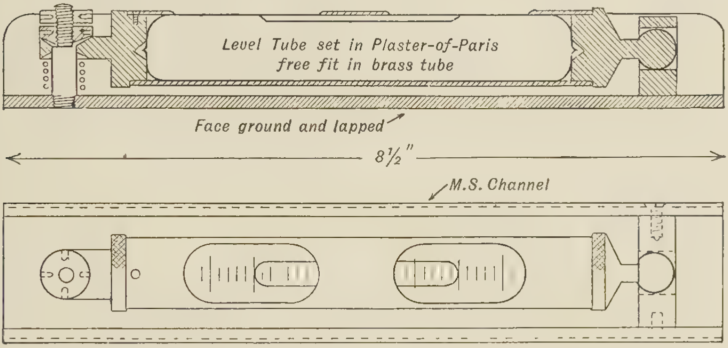


FIG. 231.

Autocollimation Tests for Straightness.

This test is somewhat similar to that described above, except that any tilting of the base as it is moved across the surface to be tested is measured optically. The general arrangement of the apparatus is shown diagrammatically in Fig. 232.

The cross-wires of a telescope, focussed at infinity, are illuminated by a suitable source of light and a reflector, and the parallel beam of light emerging from the objective is directed towards a vertical mirror, mounted on a base or saddle, which is placed upon the surface to be tested. The mirror is so arranged that the reflected beam re-enters the objective and forms an image of the cross-wires in their own plane. Any tilting of the mirror which may occur as the saddle is moved along the surface is shown by a corresponding deflection of the image. The indication is not confined to tilting only about a horizontal axis. The method serves equally well to test the truth of the bed of a machine in the horizontal as well as the vertical plane. "Wind" in the surface, however, is not detected by this method, as this type of error causes the mirror to turn only in its own plane.

If F be the focal length of the objective, a tilt θ of the mirror will give rise to a movement of the image equal to $2 \times F.\theta$, the factor 2 being introduced on account of the fact that a reflected beam is deflected through twice the angle of tilt of the reflecting surface.

Movements of the image can be measured with a low power microscope or a micrometer eyepiece. The axis of measurement is arranged first horizontally and then vertically, so as to measure the two component movements, h and v, of the image (see lower diagram).

The method of computing the results is the same as that described above for the test with a level. The deflections of the image in the two directions are treated independently, and curves can be obtained for the straightness of the bed of a machine in both the horizontal and vertical planes.

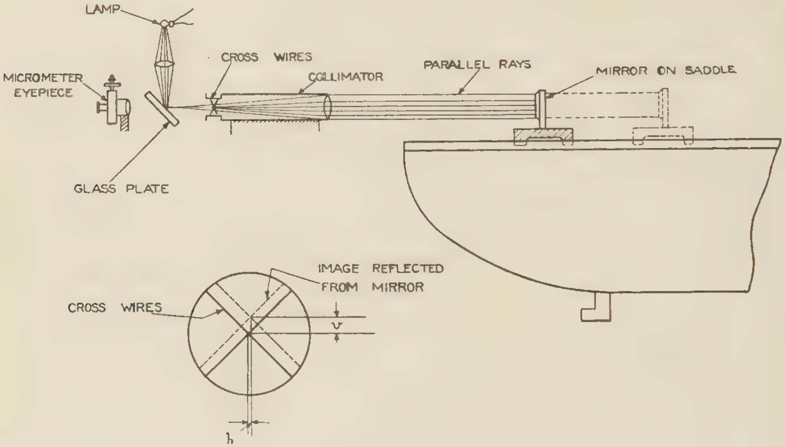


FIG. 232.

Extremely high accuracy can be obtained by this method when using a long focus objective in conjunction with a high power eyepiece.

In order to avoid double reflections at the mirror, it should be silvered on the outer surface, or consist of a polished plate of speculum. A high degree of flatness of the reflecting surface is essential for the production of a well-defined image of the cross-wires.

Tests for Flatness, using the Free Surface of a Liquid as a Standard of Reference.

The following methods of test, which have been used quite successfully by the author, illustrate how the free surface of a liquid may be utilized as a standard of flatness * against which other surfaces may be compared. Two typical cases are dealt with —(*a*) that of a fairly long and narrow bed of a measuring machine, and (*b*) a marking-off plate.

In the case of the measuring machine bed, two angle-iron troughs containing water were arranged one on each side, as in Fig. 233. The apparatus for carrying out the comparison between the surface of the bed and that of the liquid consisted of a flat plate resting across the bed and supporting a vertical micrometer head at each end over the troughs. The micrometer faces were fitted with adaptors having rounded points. The test consisted in recording the readings of the micrometers when their points had been brought into contact with the water surfaces for a series of positions along the bed. The mean of the two readings was taken for each position, and this was plotted against the various distances along the bed. The resulting diagram gave the deviations of the axis of the bed from a true horizontal line. A mean straight line through the points showed the local departures from the mean true plane. Transverse twists of the bed were detected by comparing

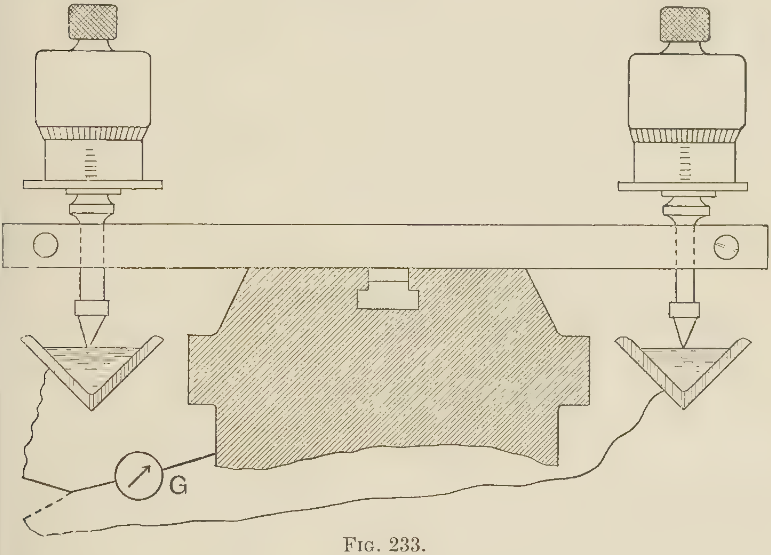


Fig. 233.

---

* The free surface of a liquid actually forms part of that of a large sphere. With its radius of about 4000 miles, however, the departure in flatness over a distance of, say, 10 feet is of the order of only 7 millionths of an inch, and can therefore be safely ignored in the present consideration.

the differences between the two micrometer readings at the various positions along the bed.

The contact of the micrometer point with the water surface was indicated electrically with the help of a dry cell and galvanometer, or telephone receiver, connected in series between the trough and the bed of the machine. A little soda was dissolved in the water to render it conductive.

At first some difficulty was experienced in obtaining consistent readings, due to a drop of water collecting on the point of the micrometer. By drying the point before each reading and keeping the surface of the water in the troughs as free as possible from dust, repetition of reading was obtained to 0·0001 inch.

The above method is only applicable when the surface is not too wide to be straddled by some convenient form of micrometer head fitting. The scheme about to be described will serve not only for fairly narrow surfaces, but also for those of larger proportions.

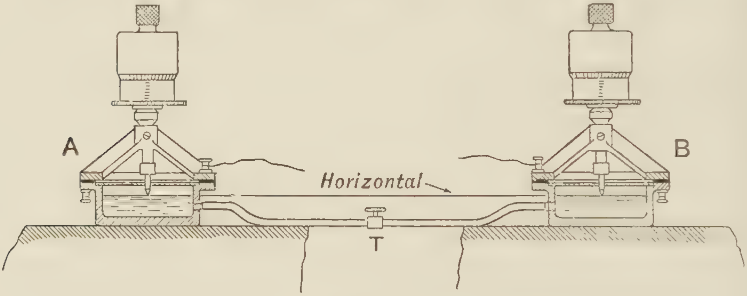


Fig. 234.

The arrangement of the apparatus is shown in Fig. 234. It consists of two similar mercury cups A and B, each of which is fitted with a bridge-piece carrying a vertical micrometer head. The two cups are connected by a stout rubber tube, so that the two mercury surfaces are at the same level. When making a test on, say, a large surface plate, it is first arranged so as to be reasonably horizontal, and one of the cups, B, is placed in a fixed position. The other cup is moved from place to place on the plate, and the contacts of the micrometer spindles with the surfaces of the mercury are read for each position in turn, using electrical indication as described above. If the volume of the connecting tube were constant, any differences in the level of the surface plate at various positions would give rise to equal but opposite changes in the two micrometer readings. Since, however, any change in the connecting tube affects the level of the mercury equally in both cups, alterations in the difference between the two micrometer readings indicate deviations of the surface plate from a true horizontal plane. If the plate as a whole is not quite horizontal, this will be indicated by the readings, and can be allowed for when plotting the results, so as to give a diagram showing the errors in flatness of the plate from its general mean plane.

In using the apparatus, it was found necessary to take certain precautions to obtain satisfactory results. The interconnecting tube must be quite free from air bubbles to establish equality of level in the two cups. It was also found desirable to insert a stopcock T in the tube. This was shut during the movement of the cup A from one position to another, so as to prevent surging of the mercury from one cup to the other, with consequent loss of time before equilibrium was re-established. The connection between the cups was, of course, restored before readings were taken. The surfaces of the mercury had to be kept clean. For this purpose glass covers with central holes for the passage of the micrometer spindles were provided for the cups, so that, having once cleaned the surfaces, they remained uncontaminated by dust.

This apparatus was used for testing the surface of a marking-off table 3 × 4 feet in size, and was found to give fairly quick and satisfactory results, reliable to within 0·0002 inch. Some slight trouble was experienced from the presence of small ripples on the mercury surfaces due to vibrations of the floor. Although these ripples were clearly visible, their effect on repetition of the contact reading did not exceed 0·0001 inch.

This method has the advantage that it can be used for quite large surfaces merely by providing a suitable length of connecting tube between the two cups.

Results of Tests on a Measuring Machine Bed.

It may be of interest to refer to the results of some tests made by the author on the bed of a measuring machine, using the following methods of test, detailed descriptions of which have been given above :

(*a*) A spirit level of 180 feet radius.

(*b*) Water troughs, as in Fig. 233.

(*c*) Autocollimation, as in Fig. 232.

A comparison between the three results can be seen from Fig. 235. The maximum difference between the curves is only 0·0002 inch, and the general agreement is within half that amount.

As regards the straightness of the axis of the bed in plan view, this was tested first by the autocollimation method. The following scheme was used afterwards to obtain a check on the results.

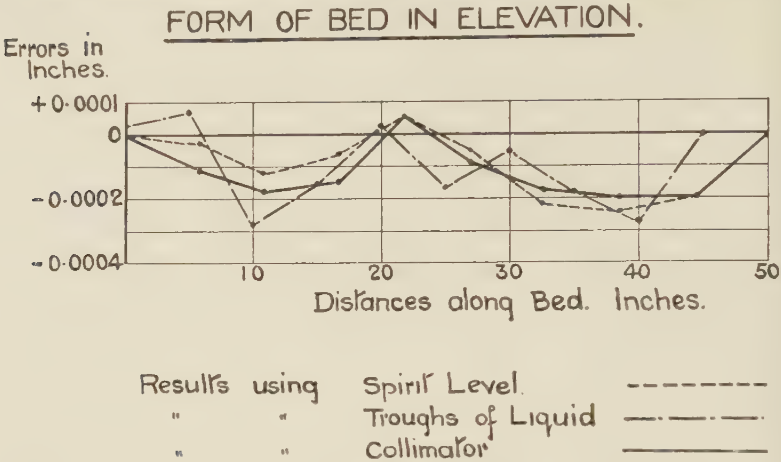


FIG. 235.

The Use of a Stretched Wire as a Datum.

A length of fine copper wire, about 0·01 inch diameter, was stretched alongside the bed on a level with the upper surface and parallel to the axis in plan view. This wire was viewed with a micrometer microscope, carried vertically in a bracket attached to the headstock of the machine, Fig. 236. Readings were taken on the wire as the headstock was moved step by step along the bed.

It was found necessary to stretch the wire quite tightly, almost to its breaking limit, before local kinks were removed. This also had the desirable effect of reducing the sag to quite a small amount, so that the focus became fairly uniform from end to end. Needless to add, the residual sag had no effect upon the accuracy of the measurements, since these were made in a horizontal plane.* The microscope measurements were plotted against the corresponding positions of the headstock along the bed, and the resulting curve is shown in Fig. 237, together with that obtained from the autocollimation method. The two results are in close agreement, and indicate a curvature in the bed amounting to 0·0006 inch at the centre.

---

* The sag of the centre of a wire stretched between two horizontal points at a distance apart L, under a tension T, is given by $s=\frac{wL^2}{8T}$, where w is the weight of the wire per unit length.

Steel piano wire, 0·01 inch dia., stretched almost to its breaking limit over a distance of 6 feet, has a sag of about 0·0015 inch. Copper wire of the same diameter would have a sag of the order of 0·006 inch over the same length.

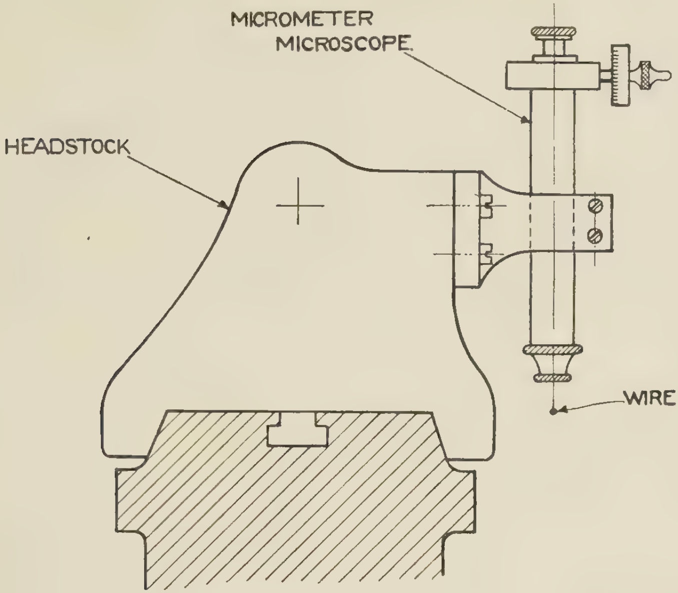


Fig. 236.

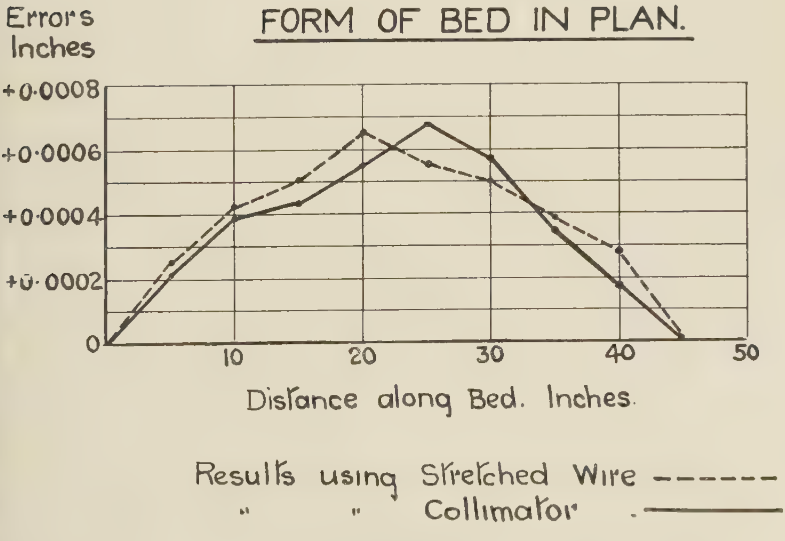


Fig. 237.

It is important to note in the test with a stretched wire that transverse twists in the bed are likely to vitiate the results unless the wire is situated on a level with the surface under examination. In that position, any transverse canting of the microscope attachment which may occur as it is moved along the surface affects only the focus of the microscope, so long as the surface is reasonably true.

Appliances by the Cambridge Instrument Co. for Testing Flatness and Straightness.

Reference should not be omitted to certain commercial instruments made by the above-mentioned company for workshop tests of flatness and straightness. The first instrument was devised in conjunction with Messrs. Richardson, Westgarth and Company, for checking the setting up of the bearers upon which turbine rotors are placed for static balancing. These bearers consist of a pair of parallel tables with surfaces 7 feet long by 8 inches wide, standing some 5 feet from the ground. The distance between the two may vary from 5 to 15 feet, according to the type of rotor to be tested. It is essential for the accuracy of the balancing tests that the surface of each bearer should be truly horizontal, and it is also desirable that the two surfaces should be in the same horizontal plane.

The test is carried out by referring the surfaces of the bearers to that of some oil contained in a trough which is laid across from one bearer to the other. For convenience, this trough may consist of the upper part of an H-girder, the ends of which are covered in with plates.

The comparisons between the metal and liquid surfaces are made with a vertical micrometer supported, in turn, off the surface of each bearer, on a tripod which straddles across the trough, as shown in Fig. 238. The reading of the micrometer when its point is brought into contact with the surface of the oil gives a measure of the distance of the bearer surface below the oil. Theoretically, it is sufficient for a test if the trough is placed in succession across the ends of the bearers at AC and BD, Fig. 239, and then either across one of the diagonals AD or BC, or else along one or other of the bearers. In practice, however, it is desirable to check the levelling in all possible positions, particularly along the length of each individual bearer, as this provides a check on the horizontality of their surfaces.

The right-angle lever to be seen at the foot of the front leg of the tripod in Fig. 238 provides a ready means, after taking a reading, of removing the point of the micrometer from the surface of the oil.

Without this it would be necessary to unscrew the micrometer for some distance to overcome the capillary effect. Before releasing this lever and allowing the foot to make contact once more with the surface, the micrometer needs to be withdrawn only a few thousandths of an inch to be ready for another setting.

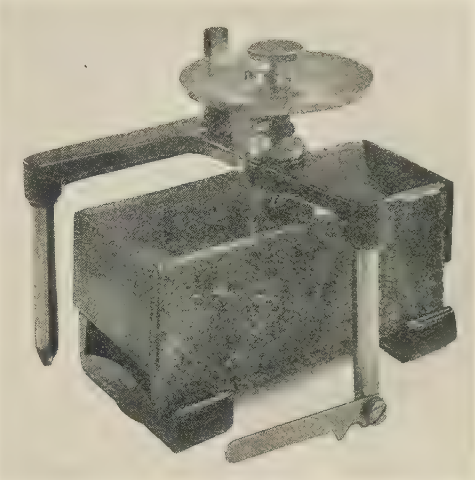


Fig. 238.

The micrometer screw has a pitch of 0·5 mm. and the disc attached to it is so graduated as to enable direct readings to be obtained to 0·002 mm.

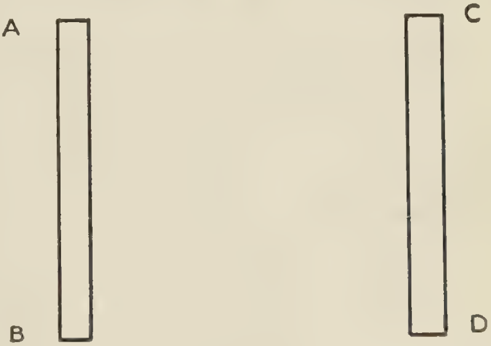


Fig. 239.

The second piece of apparatus by the same makers comprises a micrometer microscope and the necessary brackets for straining the wire to carry out the stretched wire test. Fig. 240 shows the application of this method of test to the long bed of a planing machine. In this particular test, the microscope is held on a movable bridge-piece which is supported on cylinders resting in the vee-grooves of the bed. The brackets, between which the wire is strained, are provided with fittings which are adjustable both vertically and transversely, so as to enable the direction of the wire to be set reasonably parallel to the motion of the microscope before the measurements are begun.

Test of Surfaces for Parallelism.

The following method is based upon the principles of optical reflection. The piece to be tested is placed upon a surface plate beneath a micrometer microscope, as in Fig. 241. A spider's web is

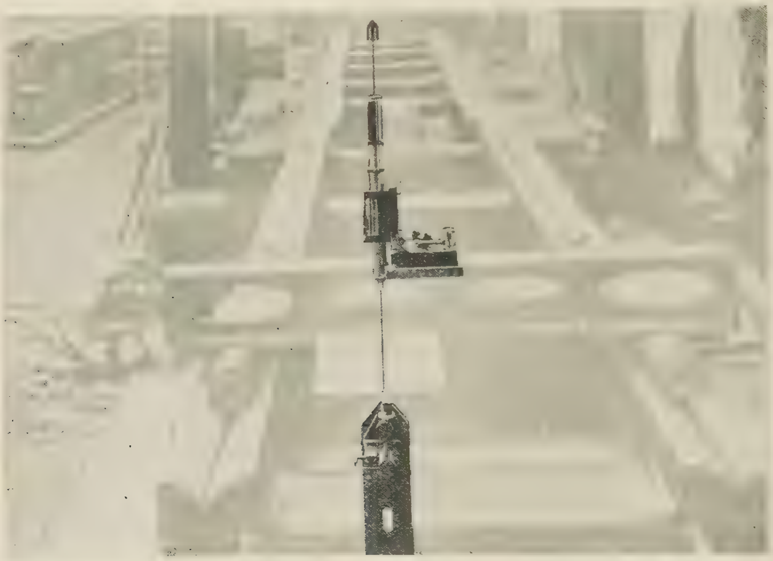


FIG. 240.

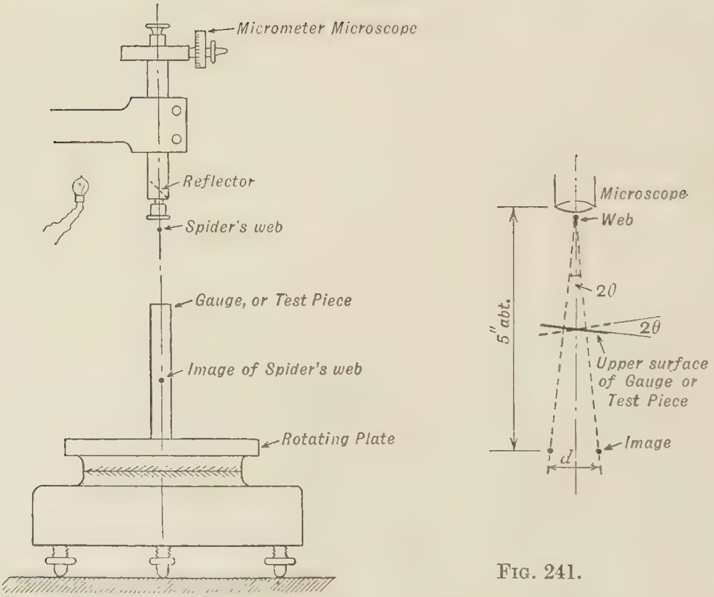


FIG. 241.

stretched horizontally in a frame just below the objective of the microscope, and the latter is focussed upon the virtual image of the web which is formed by reflection in the upper surface of the test piece.

If the two surfaces of the test piece are not strictly parallel, rotation of the piece upon its base will give rise to a corresponding transverse movement of the image of the web, and by measuring the extreme movement of the image the error in parallelism can be obtained.

With a particular microscope used by the author, the distance between the web and its image was 5 inches, as shown in the right-hand diagram, so that an error in parallelism of θ resulted in a total movement "d" of the image equal to $(5 \times 2\,\theta)$ inches. Since the magnification of the microscope was such that the position of the image could be read to an accuracy of 0·0001 inch, it was possible to detect an angular error in parallelism as small as a millionth of a radian, *i.e.*, approximately $\frac{1}{5}$th of a second of arc.

This form of test can be carried out very conveniently by using a rotatable surface plate of the type described on page 192. The test piece can then be rotated by turning the surface plate on its own base. In carrying out tests on the faces of block gauges and measuring rods, they can be wrung down on to the lapped surface of the plate, thorough contact being thereby ensured.

The results obtained when using a rotating plate would, of course, be affected by any lack of truth of the plate itself. It is desirable, therefore, to test the plate alone by observations of the reflected image in its own surface. Any error thus found can then be allowed for when making other tests. Alternatively, the effect of error in the plate can be eliminated by repeating a test after rotating the test piece through 180° in relation to the plate. The mean of the two results will give the actual error existing in the test piece.

As an example of the accuracy obtainable by this method of testing the parallelism of surfaces, Fig. 242 gives the results of measurements obtained on a rather defective $\frac{1}{4}$-inch gauge of pre-war manufacture. Instead of just measuring the total traverse of the image, its position was measured in the microscope after rotating the plate through successive intervals of 60°. The mean curve closely resembles a sine curve, as, of course, it should, seeing that the measurements correspond to linear components of the circular motion of the image.

The maximum movement of the image was nearly 0·0012 inch, which gave an error in parallelism of the two faces of 0·00012 radians. Since the diameter of the faces was 0·55 inch, this angular error corresponded to a linear error of 0·000066 inch over the diameter of the faces—a figure which checked very closely with measurements made round the periphery of the gauge in an end-measuring comparator.

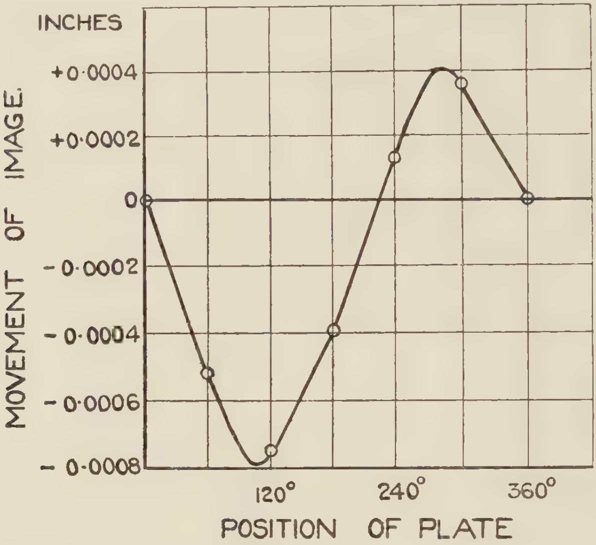


FIG. 242.

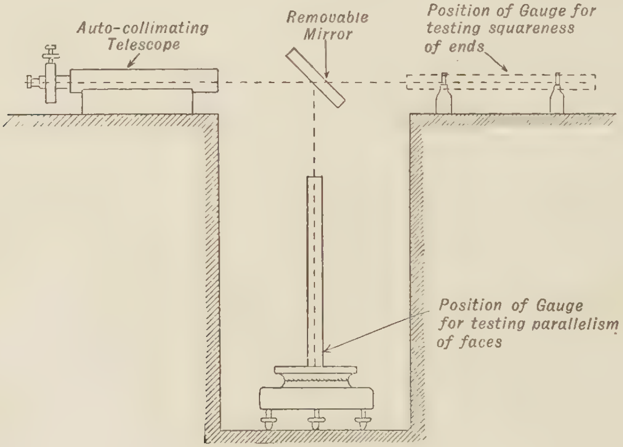

Auto-collimating Telescope
Removable Mirror
Position of Gauge for testing squareness of ends
Position of Gauge for testing parallelism of faces

FIG. 243.

The correction to the result on account of the rotating plate was negligible, since the measured error of the latter was found to be of the order of only 3×10^{-6} radians.

When using the above method for checking gauges or test pieces of different lengths, it is necessary to alter the distance between the microscope and the rotating plate so that the image of the web can always be seen. To avoid this, an arrangement such as that shown in Fig. 243 could be used, the microscope being replaced by an autocollimating telescope with a micrometer eyepiece and illuminated cross-wires. Referring to rod gauges in particular, the distance between the reflecting face of the gauge and the telescope would then be immaterial, and gauges of different lengths could be tested without having to make any alterations to the apparatus. The squareness of the faces of the gauge to its axis could also be tested afterwards by placing it on vee supports with its axis in line with the telescope, and obtaining a direct image of the wires in the two faces in turn. Rotation of the gauge in the supports would then show any error in squareness of the face under observation.

ADDITIONAL REFERENCES FOR CHAPTER X

"Testing Plane Surfaces," P. E. Shaw, *Proc. Roy. Soc.*, vol. 86 A, p. 227 (1912).

"Levels and Level Bubbles," S. G. Starling, *Trans. Optical Soc.*, vol. 24, p. 261 (1922–23).

"Spirit Levels," E. O. Henrici, *Trans. Optical Soc.*, vol. 20, p. 45 (1918).

"Adjustable Spirit Level," *Amer. Mach.*, vol. 56, p. 128 E (1922).

"Spirit Levels in the Machine Shop," E. F. Creager, *Amer. Mach.*, vol. 62, p. 160 (1925).

"On the Motion of Level Bubbles," J. Bonsdorff, *Zeit. für Instrument.*, vol. 28, p. 344 (1908).

"A New Autocollimator," F. E. Wright, *Jour. Optical Soc. of Amer.*, vol. 9, p. 187 (1924).

"Autocollimation Telescope," *Zeit. für tech. Phy.*, vol. 3, p. 225 (1922).

"Autocollimating Telescope," *Proc. Amer. Soc. Test. Materials*, vol. 23, II. p. 608 (1923).

"Optical Aligning Instrument" (Review of Patent No. 240,426, Carl Zeiss), *Machinery*, vol. 27, p. 529 (1925).

"Levelling Micrometer for Testing Machine Tool Beds," *Machinery*, vol. 18, p. 241 (1921).

"Levelling Micrometer for Testing the Balancing of Turbines," *Engineering*, vol. 110, p. 210 (1920).

"Accuracy of Long C.I. Straight-Edges," M. H. Ball, *Amer. Mach.*, vol. 53, p. 732 (1920).

"Care of C.I. Straight-Edges," E. A. Dixie, *Amer. Mach.*, vol. 52, p. 1341 (1920).

"Optical Equipment for Testing Flat Surfaces," *Amer. Mach.*, vol. 53, p. 187 (1920).

"The Optical Flat—A Practical Measuring Tool," H. L. Van Keuren, *Amer. Mach.*, vol. 53, p. 107 (1920).

"Prüfung der Gradlinigkeit und Ebenheit," F. H. Bopp, *Zeit. für Feinmech.*, vol. 34, p. 111 (1926).

"The Contouring of Smooth Surfaces," J. P. Andrews, *Jour. Sci. Inst.*, vol. 5, p. 209 (1928).

"Stirk Method of Alignment Checking," *Amer. Mach.*, vol. 64, p. 102 E (1926).

"Testing Flatness with Gauge Blocks," J. R. Godfrey, *Amer. Mach.*, vol. 65, p. 1059 (1926).

CHAPTER XI

OPTICAL MEASURING INSTRUMENTS

VARIOUS optical measuring instruments and devices have already been described in the earlier chapters of this volume and in the previous volume dealing with standard gauges. Other optical instruments particularly associated with the measurement of screw threads will be referred to in Vol. III., when that branch of measurements is being considered. In the present chapter it is proposed to describe certain types of optical instruments which are of interest from the point of view of accurate measurements. The application of optical projection methods to gauge-testing and other uses will also be dealt with.

Travelling Microscopes.

(i) *The "Cambridge" Measuring Microscope.*—This instrument, which is one of the series of engineering instruments produced by

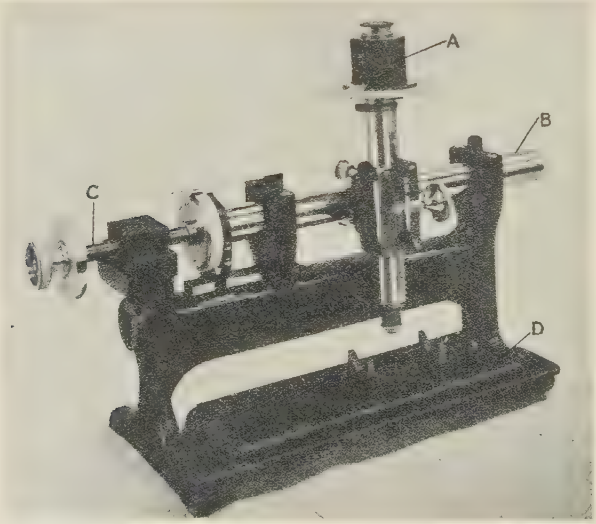


FIG. 244.

the Cambridge Instrument Co., is of simple, robust construction, and was designed for use in the workshop as well as in the testing laboratory. The general arrangement is shown in Fig. 244. The microscope A can be clamped in any position between the vertical and horizontal to a tube B, which is supported in vees, and can be traversed through a range of 40 mm. by a micrometer screw C, the nut of which is rigidly attached to the frame of the instrument. The work is normally placed upon a table D provided with geometric supports and aligning adjustments. A pair of vee blocks can be used for carrying cylindrical work.

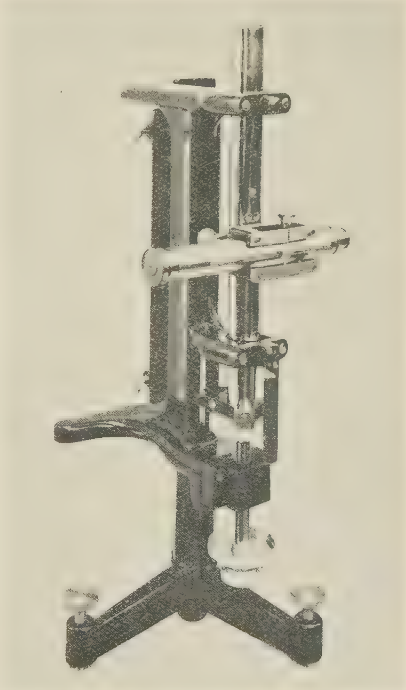


FIG. 245.

The microscope can be fitted with either ordinary cross-wires, or a goniometric eyepiece reading to five minutes of arc, as shown in the illustration. The knurled head for focussing is attached to a grooved spindle, which is pressed into contact with a cylindrical rod screwed to the microscope tube. The friction between the groove and the rod is sufficient to enable the microscope to be raised or lowered smoothly in its geometric bearing, and to maintain the position of the microscope after adjustment.

The micrometer screw has a pitch of 1 mm. and carries a drum bearing 100 divisions, each of which, therefore, represents a movement of the microscope of 0·01 mm. The thrust of the screw is communicated to the sliding tube B by a strut whose spherical ends rest in conical seatings in the end of the screw and the tube, after the manner of Fig. 295, p. 278. The contact is maintained by the tension of a long spring housed inside the tube. The tube is prevented from rotating by a projecting arm, the rounded end of which bears against a hardened plate which can be profiled so as to compensate for errors in the pitch of the micrometer screw.

This instrument can also be arranged for measuring vertical distances by mounting it, as in Fig. 245, on a tripod base fitted with levelling screws.

The principle of alignment, referred to on p. 271, is not followed out in the design of this instrument. Nevertheless, the cylindrical form of carriage offers good opportunity for obtaining the true linear traverse, which is necessary if the displacements at the focal point of the microscope are to correspond exactly to the movements of the micrometer.

(ii) *La Société Genevoise Measuring Microscope.*—The small type of jig-boring machine illustrated in Fig. 134, p. 112, can readily be adapted for measurement purposes by replacing the drilling spindle with a microscope, as in Fig. 246. From the description of the machine given on the page quoted, it will be seen that the range of movement of the table is 4 inches, and that the circular table, controlled by its accurate tangent screw, permits of angular measurements to half a minute of arc. By using the linear and angular movements in conjunction with each other, the machine can be used for determining the relative positions of parts of jigs, position gauges, etc., in polar co-ordinates.

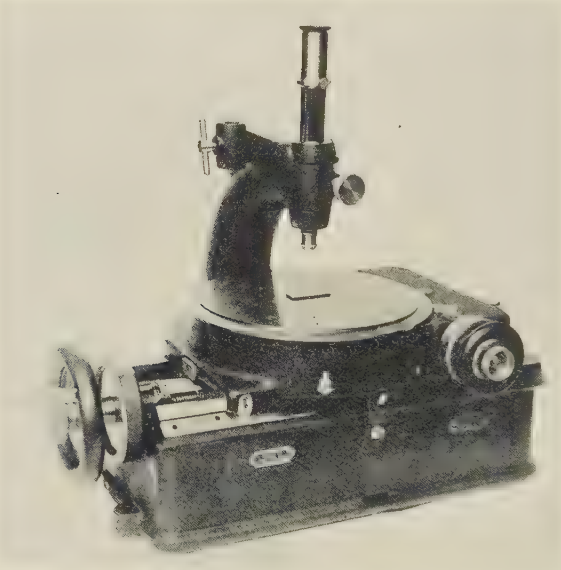


Fig. 246.

(iii) *The N.P.L. Travelling Microscope.*—This instrument, which was designed and constructed in the Metrology Department of the National Physical Laboratory in 1922 for precise linear measurements, possesses several novel features in comparison with other travelling microscopes of existing types. The principal feature making for accuracy is that the instrument is so arranged that the line of travel of the focal point of the microscope is collinear with the axis of the micrometer screw. Errors due to inherent imperfections in the "ways" of the bed or to its elastic or secular distortion are thereby eliminated.

A second important feature is the facility with which the traverse of the microscope can be read to equal accuracy in either inch or metric units.

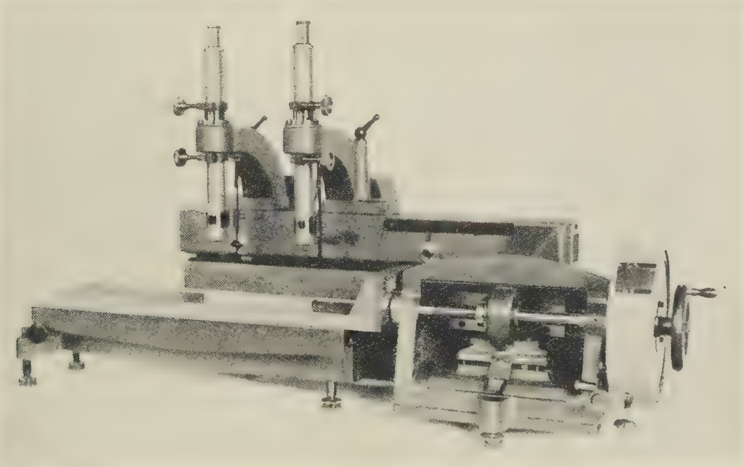


FIG. 247.

A general view of the machine is shown in Fig. 247. The bed rests on three levelling screws, and consists of a rectangular portion at the back, about 2 feet 6 inches long, having a vee-groove throughout its length, and a second portion at the right-hand end which carries the micrometer screw. The table carrying the work is placed in the rectangular space in front of the machine and to the left of the micrometer screw. In special cases the table can be removed, and work of larger dimensions placed directly on the bench. Two microscopes are provided. Each is held in a bracket which can be clamped at any position along a carriage provided with two wheels which run in the vee-groove along the back of the bed. This carriage has an arm projecting forward at the right-hand end. The outer end of the arm is supported off the bed on balls, and carries the nut which engages with the micrometer screw. The latter has a buttress thread ; the nut is supported by the arm, so that it makes contact with the screw only on the upright flanks of the threads. A ball thrust is provided at the left-hand end of the screw, the contact being maintained by the tension of a cord attached to the arm of the carriage and passing over a pulley to the left.

The machine has a corrector bar to compensate for pitch errors of the micrometer screw. The arrangement is of the usual form, in which the angular position of the nut in its housing is controlled by a radius arm, the outer end of which bears on the corrector bar.

The micrometer screw has a range of 6 inches, so that measurements up to this length can be made directly. It is possible to deal with lengths up to 12 inches by resetting the microscope at a second position along the carriage. The two microscopes provide a means of making longitudinal comparisons between two scales placed in line, one microscope reading on each. In this case, one or both of the microscopes would be fitted with a micrometer eyepiece for measuring the differences, and the micrometer screw of the machine would be used merely to translate the microscopes from one pair of lines to another.

The work table consists of a base supported on three levelling screws and carrying a plate on its upper surface. The latter can be rotated in a horizontal plane, for purposes of alignment, by pivoting about a spherical support at one end. The upper surface of this plate has two parallel vee-ways along its length, which form guides for a moving carriage supported on balls. The carriage has a flat surface on which the work is placed. At its right-hand end it has a short vertical portion faced with a hardened steel plate which butts against a steel ball fixed to the bed of the machine opposite the end of the micrometer screw. The contact is maintained by the tension of a cord, and by this arrangement there is no risk of any relative motion between the work and the abutment of the micrometer screw during the measurements.

The intermediate plate and the carriage of the table are slotted almost from end to end so as to permit of transmitted illumination in the case of transparent scales.

In addition to the long carriage on the table, a shorter one, about 8½ inches in length, can be used in conjunction with end gauges having flat faces. These are placed in one of the vees cut in the upper surface of the intermediate plate, so as to form distance-pieces between a ball fixed to the right-hand end of the short carriage and the abutment ball on the bed of the machine. By this means, the carriage can be accurately traversed through definite distances. This is useful for certain classes of measurements. The scheme may also be utilized for giving a calibration of the micrometer screw in terms of end standards. In the latter case, observations are made with one of the microscopes on a line scribed on a plug inserted in the top face of the carriage.

The micrometer screw has a pitch of 20 threads per inch and is furnished with an arrangement of three graduated drums, connected by gearing, by means of which it is possible to read the traverse of the microscope to either 0·00001 inch or 0·0001 mm. with equal facility. The arrangement is based on the relationship 1 inch = 25·4 mm., which is correct to within one part in a million. A detailed description of this part of the machine will be found in Vol. I. p. 280, where it is considered in connection with the headstock of an end-measuring machine.

Rectangular Co-ordinate Measuring Microscopes.

In addition to the ordinary type of travelling microscope where the measurements are confined to only one direction, there is another type of machine in which measurements can be made under a microscope in two directions at right angles. These machines serve many useful purposes, such as the relative location of parts of jigs.

(i) *La Société Genevoise Co-ordinate Microscope.*—A small instrument of the type just mentioned, made by La Société Genevoise, is shown in Fig. 248. The vertical microscope is arranged over a table which can be moved in two directions at right angles by means of micrometer screws. The central part of the table can also be rotated

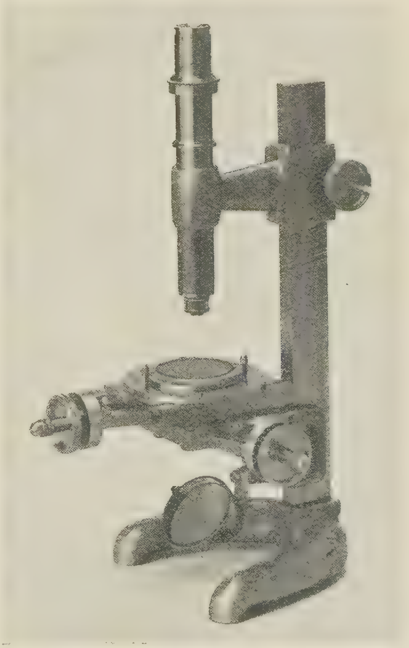


Fig. 248.

for purposes of angular measurements, a circular scale being provided reading to 10 minutes of arc. The micrometer screws have a pitch of either 1 mm. or 0·05 inch, and the graduated drums read to either 0·001 mm. or 0·00005 inch.

The microscope has fixed cross-wires, and gives a magnification of 25 times. To facilitate the measurements of transparent objects such as photographic plates, the central portion of the table is made of glass, and a suitable reflector is provided underneath to enable transmitted light to be used. This feature of the instrument is also found useful when measuring the mesh of wire gauze or fabric.

By fitting the microscope provided into the tool holder of the jig-boring machine illustrated in Fig. 136, on p. 115, that machine can be adapted for co-ordinate measurements over an area 8 inches × 8 inches.

(ii) *The Herbert Optical Measuring Machine.*—Another co-ordinate measuring microscope of rather larger dimensions, made by Messrs. Alfred Herbert, Ltd., is illustrated in Fig. 249. Here the microscope is carried in a compound slide, the motions of which are controlled by the two micrometer screws A and B, each having a travel of an inch. The microscope can also be rotated in its holder, and measurements of angle made on a circular scale situated just below the eyepiece.

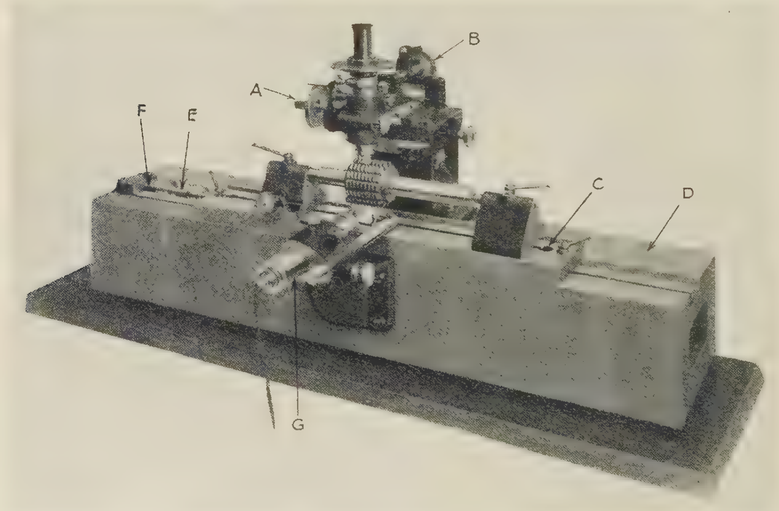


Fig. 249.

The work can be supported either on the table C or between centres, as in the case of the hob illustrated. The table can be moved along the upper finished surface of the box-shaped bed D, and measurements in the direction of the micrometer A can be extended over a range of 12 inches by displacing the table inch by inch, by means of calibrated end gauges E. These are laid in a vee-groove extending along the top of the bed, and act as distance pieces between a fixed stop F and a contact at the left-hand end of the table. The gaps between the inch displacements provided by the gauges are covered by the micrometer A.

An electric lamp G is used in conjunction with a 45°-mirror when examining the profiles of hobs, screw threads, etc., or when measuring taper gauges carried between the centres.

Zeiss Thickness Measurer.

The apparatus illustrated in Fig. 250 is intended for the direct measurement of flat-ended gauges, cylinders, balls, etc., to an accuracy of the order of 0·001 mm. The object to be measured is placed between a flat base and the end of a contact rod A having a scale B at its upper end. The rod and scale are carried in bearings,

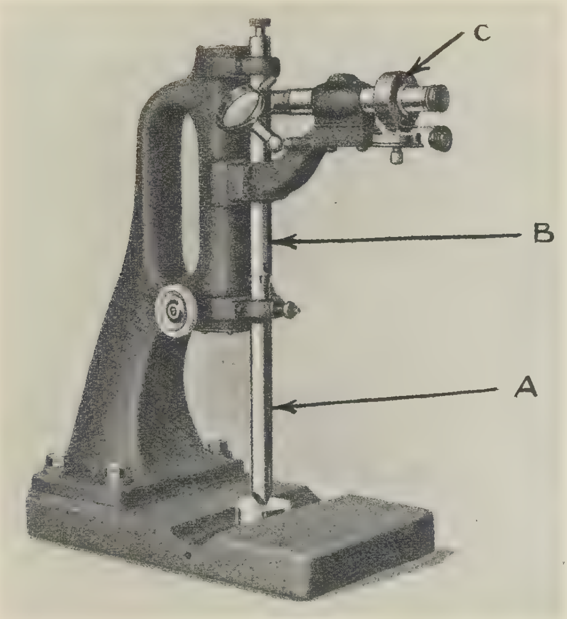


Fig. 250.

and the bulk of their weight is taken by a counterbalance weight, so that the contact pressure is quite light.

The scale is viewed with a microscope C having a micrometer eyepiece reading direct to 0·001 mm. The two parallel cross-wires of the microscope are set accurately to the nearest 0·1 mm. division on the scale, and the micrometer reading thus obtained, together with the reading of the particular line used on the scale, gives the size of the object.

The contact rod can be fitted at will with a ball, a plane face of agate, or a steel knife-edge.

Two sizes of this instrument are made, one having a range of 50 and the other 105 mm.

Zeiss Direct Reading Microscope.

Fig. 251 illustrates a simple form of microscope suitable for measuring the diameters of small holes, Brinell impressions, etc.

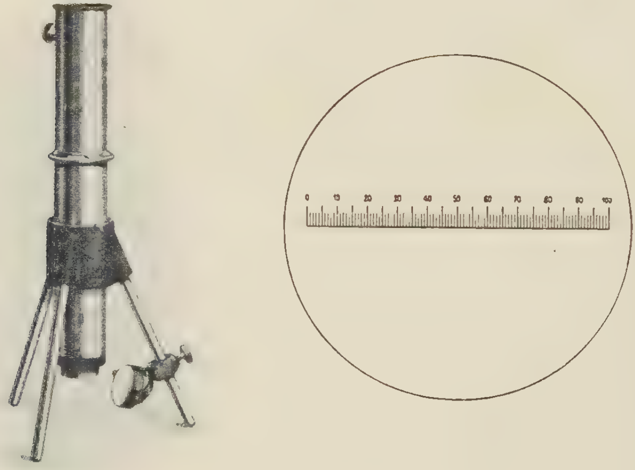
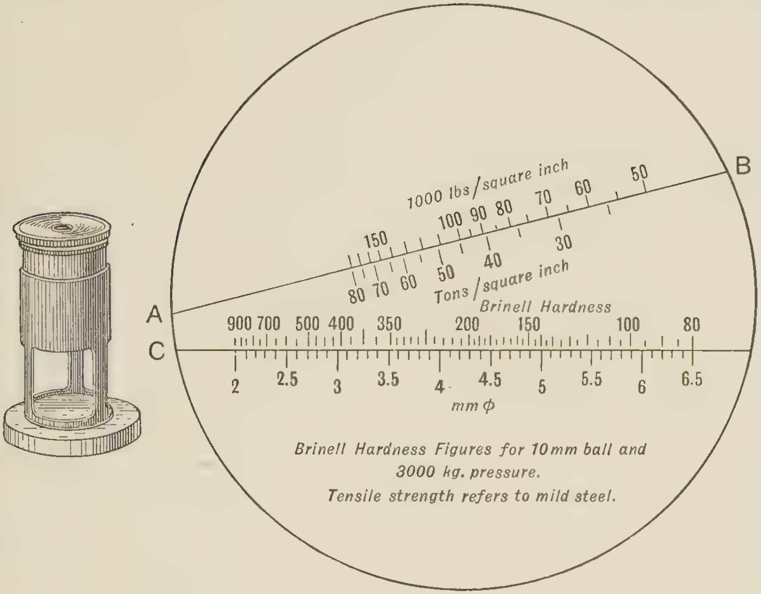


FIG. 251.

The measurements are made under a magnification of 10 times by direct comparison with a finely-graduated scale contained in the eyepiece and having the appearance shown to the right of the figure.

The same makers, Messrs. Carl Zeiss, also provide a small magnifying glass, Fig. 252, particularly adapted for gauging Brinell impressions. It consists of a lens fitted to a short tube, the bottom of which carries a transparent graticule having the appearance shown.

The glass is placed over the impression which it is desired to measure, and is adjusted until the outline of the impression fits between the tapering lines AB, CD. The diameter, together with the Brinell hardness number and the corresponding tensile strength for mild steel, can then be read on the scale provided.



Brinell Hardness Figures for 10mm ball and 3000 kg. pressure.
Tensile strength refers to mild steel.

Fig. 252.

Optical Projection Apparatus

We come now to a class of optical measuring instruments by means of which a magnified image of the profile of a gauge, or other opaque object, is formed on a screen in much the same manner as with lantern slides. The image can be either measured with a scale or, preferably, compared with a suitably enlarged drawing of the correct profile placed on the screen. Any errors from correct form then become apparent, and, if desired, can be measured with a scale.

The first use of optical projection methods for measurements of gauges was made by E. M. Eden at the National Physical Laboratory in the latter part of 1915, when simple but accurate methods were in urgent demand for dealing with large numbers of screw and profile gauges. The first apparatus which Eden set up was for giving enlarged images of screw gauge profiles, and was a development of existing machines in which a microscope was used for viewing the threads. The general scheme of the apparatus is shown in Fig. 253, which is self-explanatory. The success of the apparatus depended upon the formation of an image of uniform magnification throughout and free from chromatic defects. It was only after experimenting with several combinations of objectives and eyepieces that these objects were satisfactorily attained.

The objective finally chosen was one made by Messrs. R. and J. Beck, Ltd., and marked "3D"; the eyepiece was a Kelner's Orthoscopic by Messrs. Ross. The diameter of the useful field over which no distortion could be detected when working at the magnification of 50 times was about 7 inches. To obtain a clearly defined image of the thread, it was necessary to illuminate it with a parallel beam of light which had to be inclined along the direction of the rake of the threads.

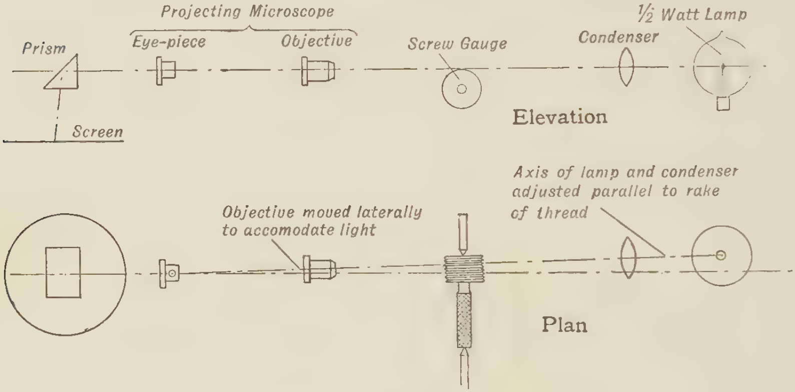

Projecting Microscope
½ Watt Lamp
Prism
Eye-piece
Objective
Screw Gauge
Condenser
Screen
Elevation
Axis of lamp and condenser adjusted parallel to rake of thread
Objective moved laterally to accomodate light
Plan

FIG. 253.

The arrangement of microscope objective and eyepiece just referred to was of no use for projecting objects larger than about $\frac{1}{8}$ inch. It became necessary to obtain other lens combinations to enable the scheme to be used for testing plate gauges, up to about $1\frac{1}{2}$ inch in size, which were required at the time in large numbers and varieties for checking the forms of the copper driving bands of shells. The accuracy of test desired on the gauges was 0·0005 inch.

As a result of experimental work, Eden found that certain high-class camera lenses of wide aperture, when combined with suitable field lenses, were capable of giving an undistorted image over a field up to 70 or 80 inches in diameter at a magnification of 50. The particular type of field lens used was a triple achromatic lens, having an aperture of about 2½ inches and a focal length of 6½ inches, made by Messrs. Ross for the objectives of binoculars. Special care had to be used in mounting the camera and field lenses, as it was found that the distortion effects depended upon the distance separating the two components. Each pair of lenses used had to be tested in an adjustable telescopic mount, in order to determine the correct separation to give the minimum amount of distortion.

Using a 6-inch focus Ross " X-press " camera lens, F 4·5, in combination with a field lens, it was found possible to deal with gauges and objects up to nearly 1¾ inch in size. For a magnification of 50, the screen was about 21 feet 6 inches away from the lens, and the working distance from the back surface of the field lens to the focal plane was 1⅜ inch. Later, it was found that the definition of the image was improved by replacing the " X-press " type of lens with one or other of the following lenses :

Ross Homocentric, F 5·6 or F 6·3,
Ross " Tessar",
Dallmeyer " Serrac ".

It should be noted that no attempt was made to design a special lens for the purpose, owing partly to the difficulty which arose in connection with the supply of special optical glass in the early days of the war. The lenses used were selected from standard types which were stocked by the makers.

N.P.L. Horizontal Projection Apparatus.

Having solved the difficulty regarding the lenses, a standard type of horizontal projection apparatus was designed at the National Physical Laboratory in 1916. This apparatus serves not only for plate gauges, but can also be used for inspecting the thread forms of screws.

(i) *The Apparatus.*—The general principle of the apparatus is extremely simple, and is shown in Fig. 254. The light is obtained from a small, right-angle pattern arc lamp 1, the crater of the arc being placed at the focus of an achromatic condenser 2. Both the lamp and condenser are supported from a pair of rods 3, which, for purposes of rake adjustment, can be rotated through about 10° in a horizontal plane on each side of the centre line, about an axis passing through the centre of the post 4, which carries the compound projection lens 5. When testing plate gauges, the lamp can be fixed in the central position by means of a pin 16. The lens post is screwed down to the bed plate 6, which carries a slide 7 on a vee and a flat machined on its upper surface. This slide carries two vertical rods 8 and 9,

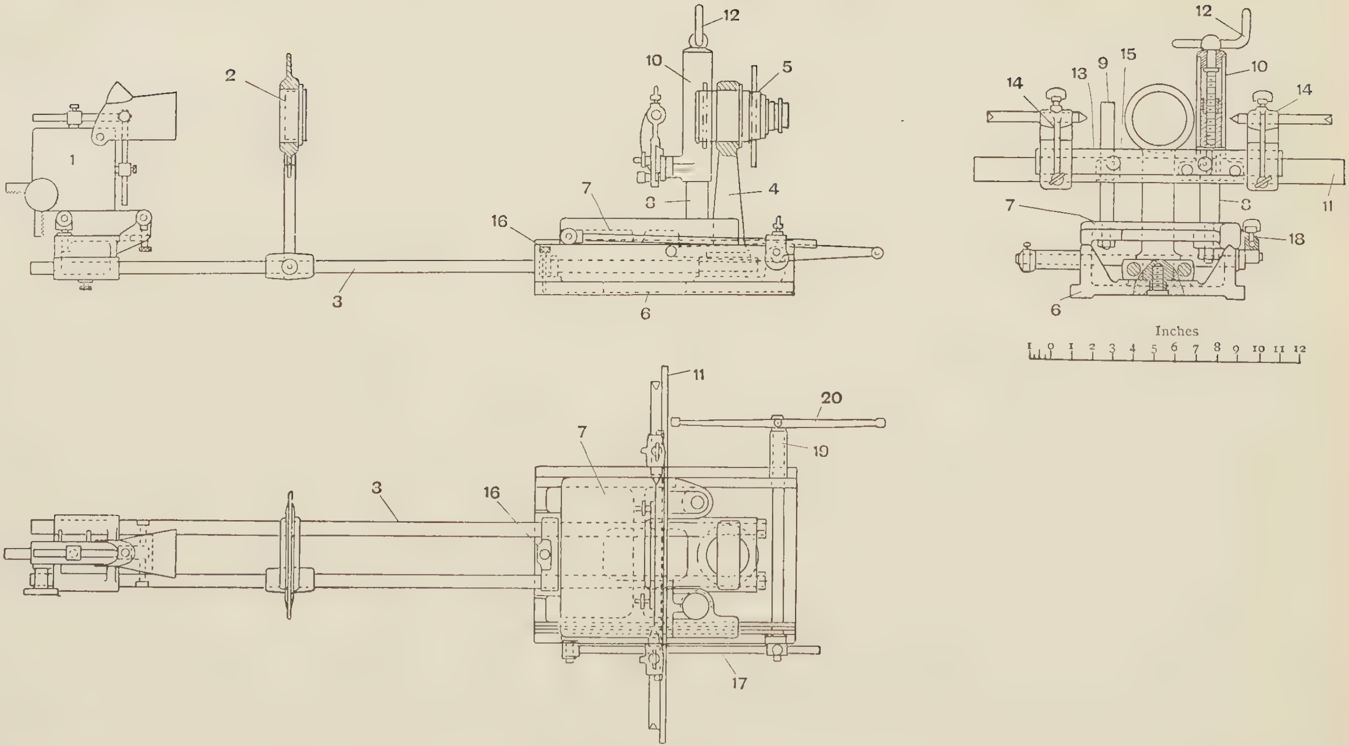

Inches
0 1 2 3 4 5 6 7 8 9 10 11 12

FIG. 254.

one of which, 8, is provided with a sleeve 10, to which is fixed a cross-bar 11. The sleeve carrying the cross-bar can be moved up and down the rod 8 by means of the screw and nut shown, a handle 12 being provided for operating the screw. A small plate, having a hole which fits the rod 9, is attached to the cross-bar 11, and prevents it from rotating. The cross-bar is provided with a slide 13, which carries a pair of centre brackets 14 and a clamp plate 15. When testing screw gauges they are held between the centres. Plate gauges are clamped between the slide 13 and the plate 15. Any special work may be stood on the upper machined surface of the slide 7. By means of the vertical movement of the cross-bar 11 and the sideway motion of the slide 13, it is possible to adjust the gauges with respect to the lens.

In order to focus the image of the gauge, the slide 7 is moved on the bed plate so as to vary the distance from the lens. This movement is transmitted from a connecting rod 17, the other end of which is clamped in a block 18 which is operated by an eccentric pin on the spindle 19. This spindle has a cross-arm 20, from the ends of which cords are taken over pulleys to the screen at the other end of the room; by pulling one or other of these cords at the screen the image can be brought into focus.

The accuracy of the results obtained by the use of this apparatus depends largely upon the alignment and squareness of the various parts of the machine, and the care which is taken in setting up the machine and the screen.

A general view of the machine is shown in Fig. 255, from which it will be seen that the apparatus itself is mounted horizontally upon a substantial wooden trestle.

For some purposes it is useful to be able to vary, at will, the magnification of the image thrown on the screen from the usual figure of 50 diameters down to, say, 10 diameters. This can be done by mounting the trestle on an under-carriage provided with flanged wheels which run on a pair of machined rails, carefully set both horizontal and square to the face of the screen. By location against a steel tape stretched along one of the rails, it is then possible to set the apparatus quite readily to any desired magnification, whilst maintaining at all positions the necessary squareness between the optical axis and the surface of the screen.

(ii) *The Screen.*—The appearance at the screen is shown in Fig. 256. The screen consists of a vertical board about 8 feet square, which is supported in a special manner so as to be movable in its own plane through a limited range. This movement is necessary

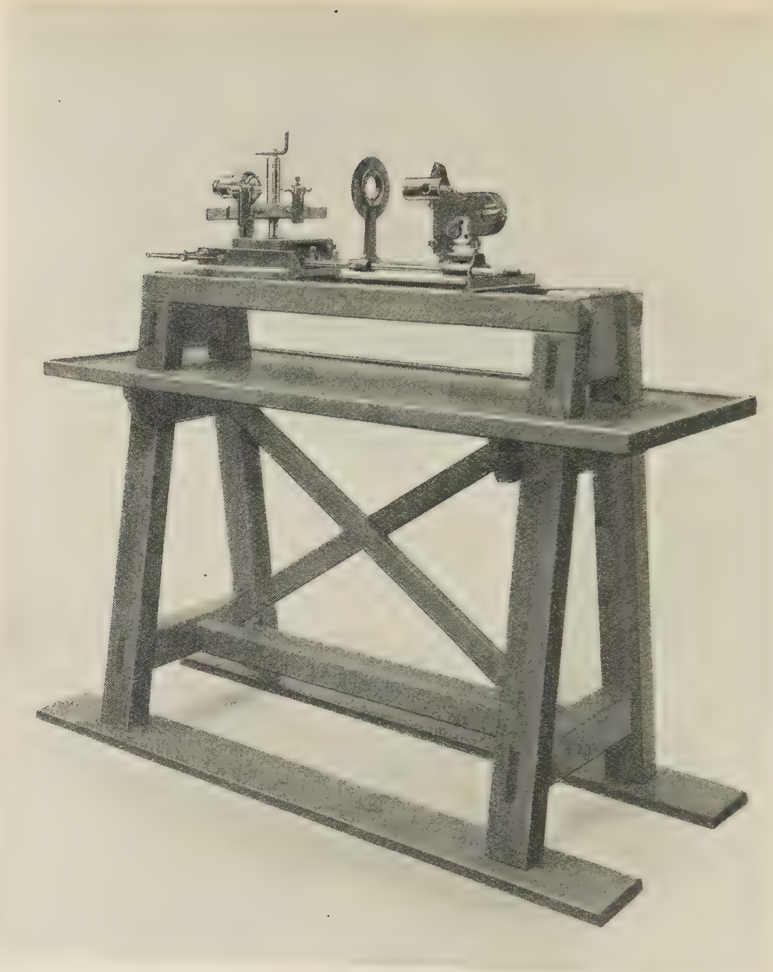


FIG. 255.

FIG. 256.

for the purpose of bringing the standard diagram of the gauge into correct superposition on the projected image. The greater part of the setting can be made by adjusting the gauge on the machine vertically and sideways, but the final adjustment has to be done at the screen itself. The latter can be moved sideways by means of levers on two horizontal bars fixed to the wall. The vertical movement is given by screw adjustments operated by two hand-wheels.

When measuring enlarged images, or their departures from a standard form on the screen of a projection apparatus, sufficient accuracy is usually obtained with a good steel scale divided preferably into 50ths or 100ths of an inch. Where greater accuracy is required, the screen can be fitted with a traversing screw having a divided hand-wheel. No great accuracy in pitch is required in such a screw, since its errors are reduced according to the degree of magnification of the image under observation.

(iii) *Diagrams.*—The diagrams of form gauges, which serve as the standards with which the projected images are compared, should be carefully drawn to the correct scale on white cardboard having a good smooth surface. It has been found that such diagrams, especially when they reach 6 or 7 feet in length, vary appreciably in their dimensions with the state of humidity of the atmosphere. Before using a diagram which has been drawn out some time before, it is desirable, therefore, to make a few check measurements on the overall dimensions.

(iv) *Special Applications of Apparatus.*—Whilst designed principally for the examination of the profiles of form gauges, cutters, screw threads and similar objects, this apparatus has been found to be a valuable tool in connection with other types of measurements, a few examples of which may be of interest.

In the method of measuring gears developed at the National Physical Laboratory by G. A. Tomlinson, an accurate pantograph is used to give a reproduction of the shape of the teeth in the form of a very fine line scribed on a smoked glass plate. The projection apparatus is used to give an enlarged image of the trace, from which it is possible to measure the errors of the tooth profile to an accuracy of 0·0001 inch. The uniformity of the circular pitch of the teeth is examined in a similar manner from a combined trace of all the teeth on a single smoked plate (see Chapter XVI. for details).

Another instance of the combined use of the pantograph and the projector is in the accurate determination of the cross section of stream-line wires, where it is not possible to obtain an enlarged image direct from the wire itself.

In a similar manner, the projector can be used for examining traces made on transparent celluloid by the gentle pressure of a steel style in certain recording instruments made by the Cambridge Instrument Company.*

The examination of wire gauze, used for accurate sieving, which formerly entailed lengthy and tiring measurements under a microscope, is facilitated by the projection method. The diameter and pitch of the wires and the uniformity of the mesh are readily obtainable by measurements and inspection of the enlarged image at the screen. Fig. 257 is a reproduction of a photograph of a small part of the image of a piece of wire gauze having nominally 180 strands per inch. The lack of equality of spacing in the two directions is rendered obvious.

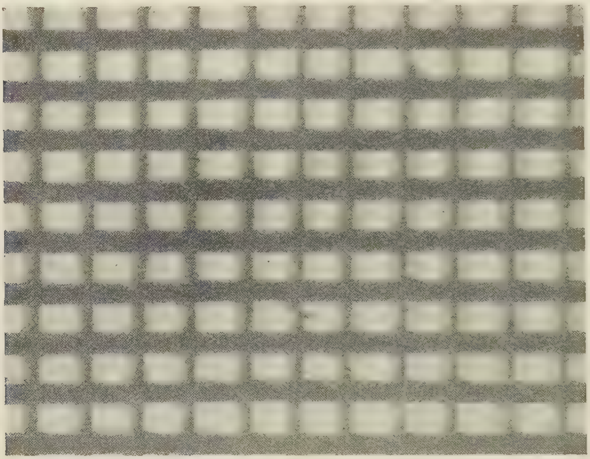


FIG. 257.

Such permanent records can be made by exposing a photographic plate or a sheet of bromide paper at the screen, the projection room being, of course, completely darkened when the apparatus is used for this particular purpose.

In a recent research, use was made of the projection apparatus by V. Stott to determine the deformation of pivots under load.† The pivot under test was mounted vertically behind the projection lens, and means was provided for applying loads to the tip. The original shape of the pivot and the deformation resulting from the application of successively increasing loads were readily obtained from the image projected on to the screen. For this particular purpose, the magnification was raised to 200 diameters by substituting a one-inch microscope objective for the usual projection lens.

---

* See *Engineering*, vol. 119, p. 271 (1925).

† See *Nat. Phys. Lab. Report* for 1925, p. 151.

(v) *Pivot Lapping in Projection Apparatus.*—The experiments just mentioned were conducted on a number of pivots having a series of different angles and radii at the tip. To facilitate their production to the required profiles, a special projection apparatus was used, in which the pivots could have their profiles kept constantly under observation during the actual process of being finished to shape in a revolving chuck.

The apparatus is shown in Fig. 258. The pivot itself is held in a chuck, which revolves with a hardened steel spindle A mounted at each end on two rings of steel balls. These balls, which are under slight radial pressure directed towards the axis of the spindle, allow the latter to rotate freely, but prevent any end-play.*

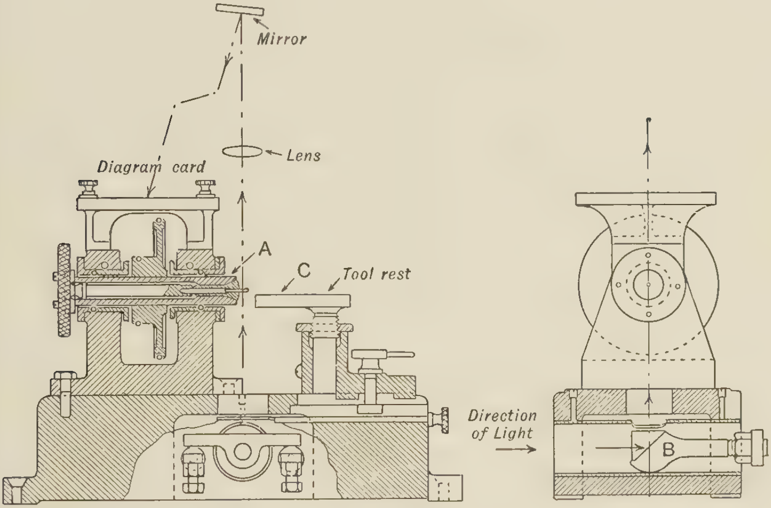


FIG. 258.

The point of the pivot is illuminated by a strong beam of light directed vertically by a reflecting prism B. After passing the pivot, the light traverses a projection lens, and, striking a mirror supported about 7 feet above, is reflected downwards, and forms an image of the pivot on a small horizontal platform just above the spindle. A diagram of the required shape enlarged to the usual magnification of 50 times is placed on this platform, and the operation of shaping the point with a slip of fine oil-stone is continued until the image fits the diagram.

---

* This type of ball-bearing spindle was designed and patented by A. J. C. Brookes.

Vertical Projection Apparatus.

The horizontal form of projection apparatus described above can be used, not only for all types of profile gauges within the compass of its field lens, but also for examining the profiles of screw threads. For the latter purpose, however, where a much smaller field suffices, Eden designed a special type of apparatus which enables screws to be dealt with in a very convenient manner. In this apparatus, which is usually known as the vertical projector, the optical axis is arranged vertically, and the light, after being reflected from a horizontal mirror overhead, forms an image on a small platform situated just in front of the observer. The gauge itself is mounted on centres and is capable of movements in the horizontal plane in directions parallel and perpendicular to its axis. These movements are controlled by micrometer screws, so that it is possible to make measurements of the pitch and diameters of the screw, as well as examine the form of its thread by simple comparison with a standard diagram.

A complete description of this apparatus, as well as others of similar form for the same purpose, will be referred to in Vol. III. under the testing of screw gauges.

The Lewbeck Projection Microscope.

This apparatus, which is made by Messrs. R. and J. Beck, Ltd., was designed for the special purpose of measuring the diameters of fine wires.

The portion of wire to be examined is held vertically between clips in front of the objective of a projection microscope, and is strongly illuminated by a beam of light derived from an electric lamp. This part of the apparatus is shown in Fig. 259. On emerging from the horizontal microscope, the light is reflected by an inclined mirror, and is brought to a focus upon a sloping ground glass screen, situated inside a hood in order to exclude extraneous light. The magnification of the image of the wire on the screen is arranged to be exactly 1000 times, so that the tenth-inch divisions of the scale marked on the screen represent ten-thousandths of an inch in the diameter of the wire. By estimation, it is possible to read off the diameter to about 0·00002 inch. A simple adjustment of the wire holder enables the wire to be turned through 90°, so as to allow a check to be made upon its circularity.

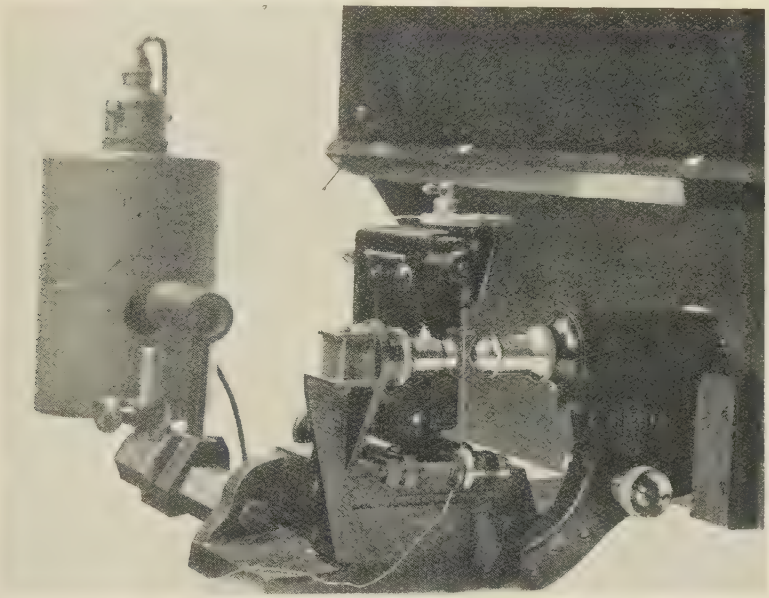


FIG. 259.

Definition of Projected Images.

It has already been mentioned that the development which has been made in gauge projection methods was based upon experimental work rather than theoretical considerations of the optical problems involved. The lenses were selected by trial from commercial stocks, and, where necessary, were suitably combined so as to give projected images free from any serious distortion. The successful results obtained by this procedure were largely responsible for the postponement of a study of the theory underlying the optical principles of the projection method. The occurrence of certain inexplicable phenomena, however, and the desire to make use of the method for more accurate purposes, led to theoretical investigations of the image formation at the National Physical Laboratory in 1924 by W. G. Ridge, and later by G. A. Tomlinson.

Attention was first directed to the case of a cylinder placed before a projection lens and illuminated by a truly parallel beam, as in Fig. 260. It is clear that, between the cylinder and the lens there must exist a sharply-defined shadow, and it might be expected that a magnified image of this shadow would be seen on the screen, the definition of the image being independent of the distance of the cylinder from the lens. In practice, however, it is found that the edges of the projected shadow are quite ill-defined unless the position of the cylinder is carefully adjusted to suit the focus of the lens, as is done in an ordinary projection lantern with transparent slides.

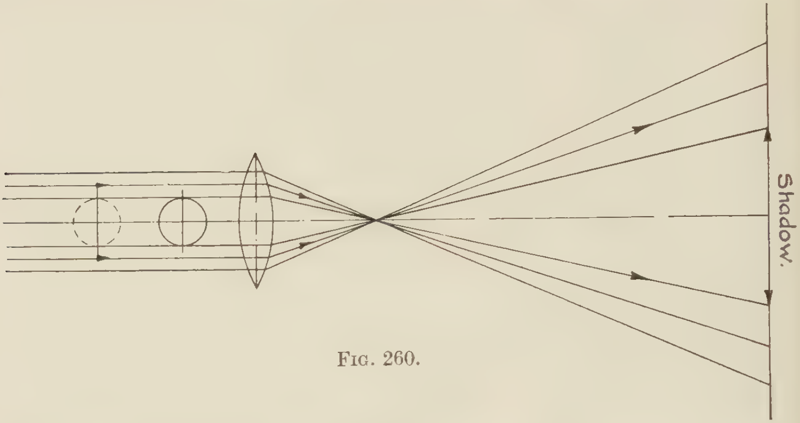


Fig. 260.

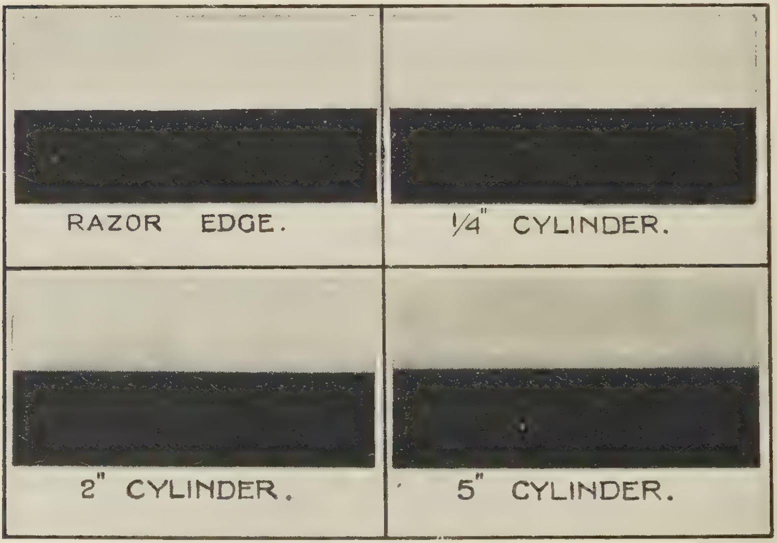


Fig. 261.

Experiment also shows that the definition of the edge of the shadow on the screen falls off with larger size cylinders or thick plates; with very small cylinders, or thin-edged plates, it is quite crisp. This can be seen in Fig. 261, which shows a series of photographs of images, at a magnification of 50 diameters, first of the edge of a razor blade and then of the profiles of three cylinders, increasing in size from $\frac{1}{4}$ to 5 inches diameter.

The illuminating beam used to obtain these photographs was derived from a small arc lamp placed at the focus of a 7-inch condenser. Owing to the finite size of the crater of the arc, the beam was not exactly parallel; in fact, the rays were distributed over an angle equal to that subtended by the area of the crater at the centre of the condenser. Let us consider first the effect of such a non-parallel beam when projecting the profile of a thick plate T, as in Fig. 262. All the rays which graze the back or the front edges of the plate are enclosed between the lines *ab* and *cd*, which represent the maximum angular divergence of the illuminating beam from true parallelism. Since these rays do not all pass through a single point, they cannot come to a definite focus on the screen. The best definition will be obtained when the minimum section of the beam at *ef* is focussed. Since this minimum width is equal to $\frac{1}{2}t \tan \theta$, the clearness of the image of the edge of the plate would be expected to improve with thinner plates and with closer approach to parallelism of the illuminating beam. This is in accordance with experiment.

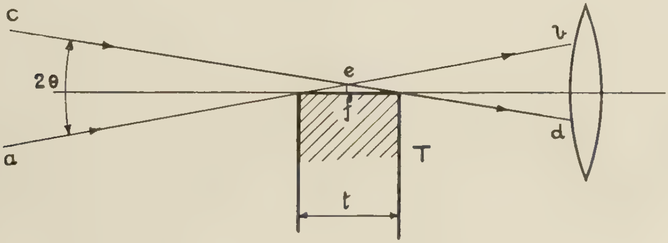


FIG. 262.

Let us return now to the familiar case of projection, that of a plain cylinder. With a non-parallel beam, the image-forming rays will graze the cylinder over a finite arc *ab*, Fig. 263, the length of which is given by the product of the maximum divergence 2θ of the beam and the radius of the cylinder. From the symmetry of the arrangement, the best definition of the image of the edge on the screen will be obtained when the focus is adjusted to suit the axial plane *cd*. The crispness of the image will depend upon the length of the arc *ab*, so that with larger cylinders, or less parallel beams, poorer definition is to be expected. This result is evident from Fig. 261 in so far as variation in the diameter of the cylinder is concerned.

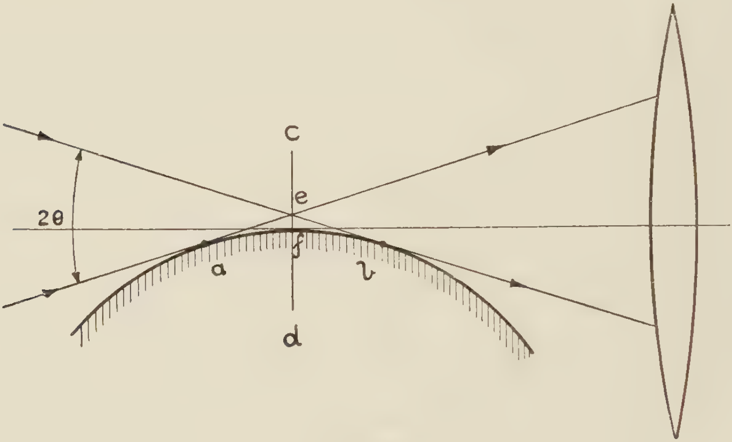


Fig. 263.

The fact that, when projecting a cylinder, the best definition is obtained when the focal plane corresponds to the axial section of the plug, has been shown by using a plug cut back to the centre line over a portion of its length, as in Fig. 264. The focussing slide of the horizontal projection apparatus used was provided with a micrometer adjustment, and readings of the distance of the slide from the lens were taken after focussing the image of the curved surface near the centre of the plug for three positions of the plane face—horizontal, vertical facing towards the lens and vertical facing away from the lens. In addition, the position of focus was obtained for the edge of a thin razor blade held against the plane

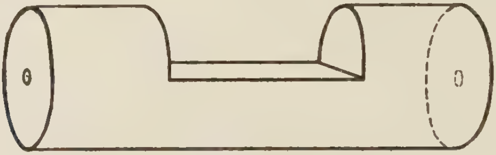


Fig. 264.

face when in a vertical position. In all four cases it was found that the readings were the same to within the possible accuracy of setting.

From the examples given in Fig. 261 of the projected images of a number of cylinders, it is noticeable that the edge of the black shadow is bordered by diffraction lines and a bright band whose width varies according to the size of cylinder. This extra illumination is due to concentration of rays of light reflected from the surface of the cylinder facing the condenser. It is more evident in Fig. 265, which shows an image of the special cylinder (Fig. 264) in the region where the complete cylinder joins the portion cut away. The bright band bordering the left half of the image, corresponding to the complete cylinder, is absent over the other half, where the plane face of the half cylinder was arranged vertically and facing the source of light.

The formation of the bright band will be gathered from Fig. 266 (p. 242), in which reflected rays are shown by full lines, whilst others responsible for the general illumination of the lower half of the screen are indicated by dotted lines.

FIG. 265

The gradual concentration of the reflected rays as one moves from the screen towards the lens can be shown on the projector by traversing a small screen in that direction. The bright band will then be seen to narrow down to a minimum width and increase in brilliancy at a position corresponding to AB. If, therefore, a narrow obstruction be placed at AB, the whole of the bright band bordering the projected image on the main screen can be removed if desired.

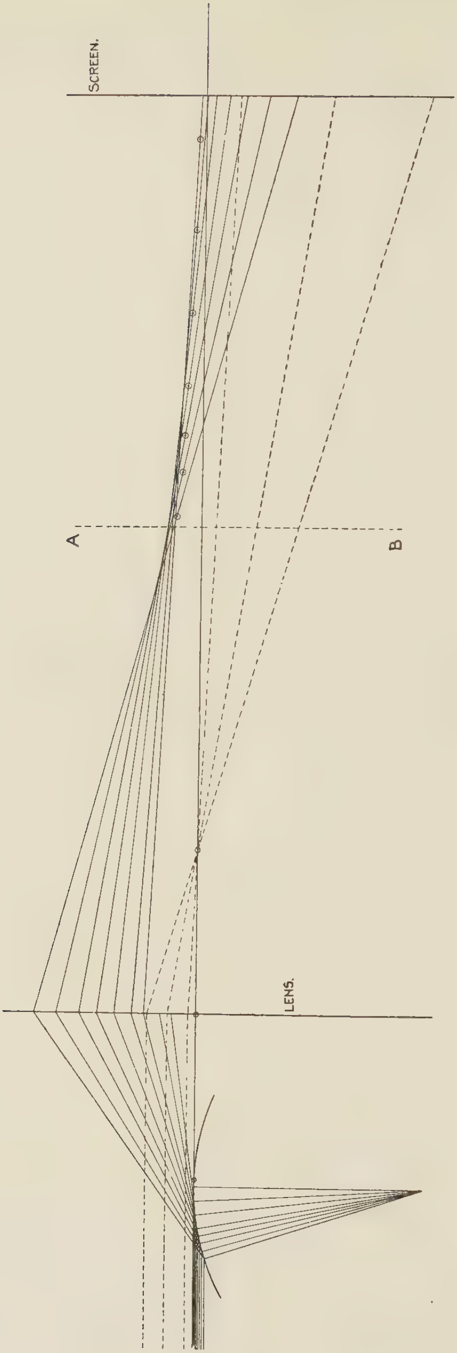


FIG. 266.

ADDITIONAL REFERENCES FOR CHAPTER XI

"Use of Microscopes in Gauge Section of Bureau of Standards," *Amer. Mach.*, vol. 51, p. 581 (1919).

"Bausch and Lomb Toolmakers' Microscope," *Amer. Mach.*, vol. 65, p. 652 (1926).

"Micro-Telescopic and Super-Microscopic Apparatus for the Engineering Shop," *Amer. Mach.*, vol. 47, p. 184 E (1918).

"Workshop Microscope," *Amer. Mach.*, vol. 46, p. 71 E (1917).

"Principles and Advantages of Optical Methods for Measuring Machine Parts," H. F. Kurtz, *Mechanical Engineering*, vol. 47, p. 987 (1925); *Amer. Mach.*, vol. 63, p. 894 (1925).

"S.G. Measuring Microscope," *Amer. Mach.*, vol. 64, p. 177 (1926).

"S.G. Two-Co-ordinate Measuring Machine," *Amer. Mech.*, vol 69, p. 706 (1928).

"The Setting of Microscope Cross Wires," A. Pérard, *Rev. d'Optique*, vol. 2, p. 506 (1923).

"The Errors of Micrometer Microscopes," A. W. Gray, *Sci. Papers of Bureau of Stds.*, vol. 10, p. 375 (1913).

"Neue optische Messverfahren für den Werkzeug und Maschinenbau," A. Steinle, *Maschinenbau*, vol. 9, p. 244 (1924).

"Optical Methods of Setting Work and Tools," *Machinery*, vol. 28, p. 97 (1926).

"Optische Messverfahren in der Werkstätte," Dr. Max Kurrein, *Zeit. für Feinmech.*, vol. 29, pp. 73, 83, 99 and 108 (1921).

"A Precision Measuring Device," *Amer. Mach.*, vol. 69, p. 215 (1928).

"Optical Instrument Demands Unusual Precision," *Amer. Mach.*, vol. 68, p. 421 (1928).

"Some Optical Aids for the Engineer," A. C. Banfield, *Machinery*, vol. 14, pp. 613, 650, 705 (1919).

"Use of Optical Instruments in Machine Work," *Amer. Mach.*, vol. 56, p. 697 (1922).

Optical Measuring Instruments, L. C. Martin (Blackie and Son, Ltd., London, 1924).

"Inspection by Optical Projection," (Bausch and Lomb), *Machinery* (Amer.), vol. 28, p. 984 (1922).

"Mikrometer und Messapparate," Dr. Paul Duckert, *Zeit. für Instrument.*, vol. 44, pp. 443, 483, 547 (1924); vol. 45, p. 176 (1925).

"Hilger Optical Gauges," *Engineering*, vol. 117, p. 10 (1924).

"Measurements by Optical Projection," G. A. Tomlinson, *Proc. Optical Convention*, pt. i., p. 311 (1926).

"Improved Type of Optical Projection Apparatus," *Amer. Mach.*, vol. 53, p. 1158 (1920).

"Some Applications of Optical Projection," C. F. Smith, *Machinery*, vol. 27, p. 473 (1926).

"Zeiss Projection Optimeter," *Amer. Mach.*, vol. 68, p. 123 E (1928).

"Optimeter," (Carl Zeiss), *Amer. Mach.*, vol. 62, p. 109 (1925).

"Vickers Projection Microscope," *The Engineer*, vol. 137, p. 728 (1924).

"Origin of Projection Apparatus," *Amer. Mach.*, vol. 51, pp. 234, 336 (1919).

"Sieve Testing Apparatus," L. V. Judson and R. E. Gould, *Jour. Amer. Opt. Soc.*, vol. 6, p. 719 (1922).

"Optical Method for Testing Wire Mesh," D. P. Muirhead, *Amer. Mach.*, vol. 62, p. 785 (1925).

"Optical Strain Gauges and Extensometers," L. B. Tuckerman, *Proc. Amer. Soc. for Testing Materials*, vol. 23, pt. ii., p. 602 (1923).

"Roller Extensometer for Longitudinal and Lateral Strains," Lamb, *Engineering*, vol. 119, p. 207 (1925).

"Sensitive Optical Lever for Measuring Coefficient of Expansion," *Jour. of Sci. Insts.*, No. 7 (1924).

"Measuring One-thousand-millionth of an Inch," *Machinery*, vol. 32, p. 104 (1928).

"An Optical Method of Measuring Small Vibrations," H. A. Thomas and G. W. Warren, *Phil. Mag.*, vol. 5, p. 1125 (1928).

"The Double Suspension Mirror," L. Southerns, *Phil. Mag.*, vol. 36, p. 477 (1918).

"Die Parallelität der Messflächen verschiedener Messgeräte," Dr. Berndt, *Zeit. für Feinmech. und Präzision*, vol. 35, pp. 245, 256 (1927).

CHAPTER XII

ELECTRICAL DEVICES USED IN MEASURING

Perhaps the simplest application of electricity in connection with linear measurements is as a means of indicating contact between a fixed and an adjustable part of a measuring device. A typical example occurs in the micrometer headstocks of the Shaw measuring machine.* Here, the establishment of contact between the tip of the advancing micrometer spindle and the measuring plunger is indicated by the closing of an electrical circuit containing either a galvanometer or a telephone receiver.†

Although it is a simple matter in such cases to arrange for the contact to take place at platinum points, sparking inevitably occurs and is often the cause of erratic readings. This difficulty can be avoided, however, by using a scheme due to G. A. Tomlinson,‡ where the current passing through the contact is made extremely small.

Tomlinson's Grid Contact.

This method takes advantage of the variation produced in the anode current of a thermionic valve by a change in the potential of the grid. The contact A (Fig. 267) is placed between the filament and the grid of the valve, in series with a few dry cells B. On closing the contact, the potential of the grid is raised from G_1 to G_2 on the characteristic diagram, with the result that the anode current, which can be measured by a milliammeter or galvanometer C, is increased from A_1 to A_2. By suitably adjusting the initial potential of the grid by means of the potentiometer D and the voltage of the auxiliary battery B, the valve can be made to operate over the steepest part of its characteristic curve, and thus produce the maximum desired effect.

---

* For description, see Vol. I. p. 270.

† If a telephone receiver is used for such a purpose, it is desirable for the battery circuit to include an automatic make and break, so that the making of contact is signified not by a solitary click heard in the telephone, but by a succession of clicks due to the make and break. A single click can easily be missed, and the micrometer overrun, with possible damage to the measuring instrument.

‡ *Phil. Mag.*, vol. 44, p. 870 (1922).

After breaking the contact at A, it will be understood that it is necessary to restore the grid potential to its normal value before a second indication of contact can be obtained. This can be brought about automatically by inserting a high resistance "grid leak" E into the circuit.

The great advantage of this scheme lies, of course, in the very small current (only a few microamperes) which passes across the contact. In addition, variation in the resistance of the contact within wide limits has no appreciable effect upon the operation of the valve, owing to the very high resistance of the circuit between the filament and the grid.

Used as a relay, the scheme has the further advantage that very little pressure is required between the contacts in order to produce the change in anode current. Tomlinson has ascertained that a contact force of only 0·000001 grm. is required to charge the grid. Moreover, owing to the very small current which passes across the contact, there is no objectionable tendency for the contacts to adhere together, and the relative movement between the points can be reduced to as small as 0·001 mm. if desired.

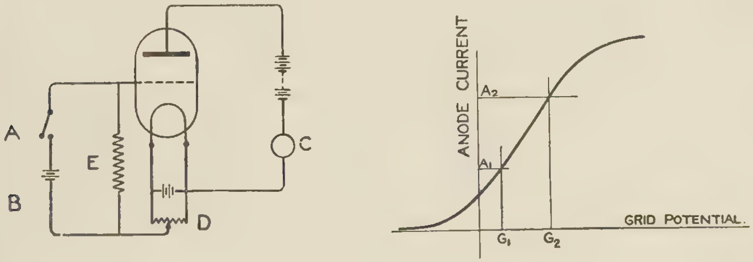


FIG. 267.

Sensitive Measuring Device depending upon Electrical Contact.

It may be of interest at this point to refer to a very simple device for making accurate measurements, the success of which depends upon the registration of electrical contact between two parts of the apparatus. The principle of the scheme will be gathered from Fig. 268. A tripod, carrying a scale pan and provided with a ball-ended measuring point on the underside, has its three insulated feet resting on a surface plate. To compare the sizes of two gauges, for example, they are placed in turn on the surface plate under the measuring point, and the scale pan is loaded with weights until contact occurs between the ball point and the upper surface of the gauge, as indicated electrically. The difference between the weights required for the two gauges gives a measure of the variation between their sizes. The apparatus can be readily calibrated by taking observations on a series of gauges of known differences. For reasonable loading the calibration curve follows a straight line.

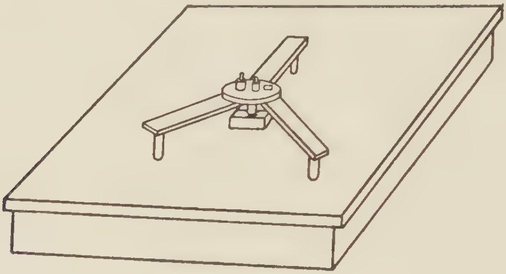


FIG. 268.

The appliance can be made to assume almost any degree of sensitivity by suitably varying the stiffness of the tripod.

Rayner's Application of Valve Circuit.

In some experiments carried out before the Physical Society of London,* Dr. E. H. Rayner indicated a method of using a thermionic valve as an indicator of small relative displacements between bodies. The method is based upon the well-known fact that the anode current of a valve is altered by varying the potential of the grid, but is unique as regards the method of changing the potential.

Dr. Rayner found that by virtue of the change produced in the potential of the grid, a metal plate or wire, connected thereto, acts as a sensitive indicator of the presence of an electrical field in the neighbourhood. For example, if a negatively-electrified object, such as a piece of ebonite, be brought close to the metal conductor, the anode current may be reduced practically to zero. The grid in this case receives a negative charge by induction.

Dr. Rayner considered it possible to use a valve on these lines as a sensitive indicator of small relative displacements of metal surfaces, provided they can be insulated from one another and charged to different potentials.

---

* *Proc. Phy. Soc.*, vol. 38, p. 335 (1926).

Whiddington's "Ultra-micrometer."

The following scheme, in which high frequency oscillatory circuits are used for detecting minute changes in the relative positions of a pair of metal plates, is due to Professor R. Whiddington.

In diagrammatic form the scheme is as shown in Fig. 269. The oscillatory valve circuit A includes in the anode circuit a parallel-plate air condenser P. Variations in the capacity of this condenser alter the frequency of the electrical oscillations, which are arranged to be of the order of a million per second—a frequency which, in itself, is far too high to produce an audible note in the loud-speaking telephone T. Interaction between the circuit A and a similar oscillatory circuit B, the frequency of which can be adjusted by varying the condenser C so as to be nearly, but not quite, equal to that of A, causes a series of beats to be set up in the telephone circuit, the frequency of which is such as to produce an audible note. Since the frequency of the note is equal to the difference between the frequencies of the two circuits, it will be readily understood that a relatively small change in the frequency of A will produce a marked alteration in the pitch of the note emitted by the telephone. For example, if the frequencies of the circuits A and B are 1,000,256 and 1,000,000 per second, the note would be of the same pitch as that given by the middle C of a piano, the frequency of which is 256 per second. If the frequency of A be increased to 1,000,288 per second, the pitch of the note would rise to that of D on the musical scale, *i.e.* through a whole tone.

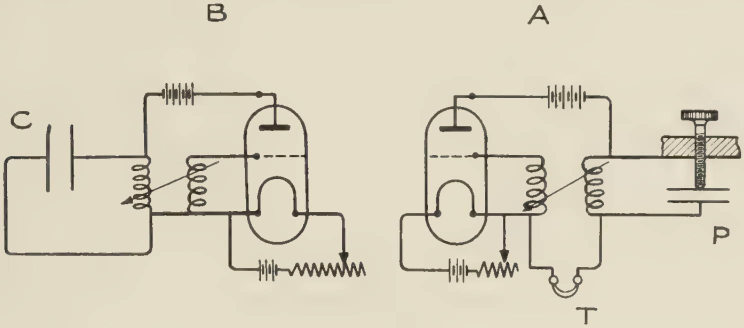


FIG. 269.

By making further use of the principle of " beats ", a change of even less than unity in the frequency of A can be detected. This is done by setting up a third oscillatory valve circuit containing capacities and inductances so large as to produce by induction an audible note in the telephone. This note can be adjusted both in pitch and intensity by varying the tuning of the third circuit so as to produce beats with the heterodyne note derived from the interaction of circuits A and B. Since it is a simple matter to observe a variation of one per second in the frequency of such beats, it follows that a difference of the same magnitude in the frequency of the circuit A can be detected.

To test the sensitivity of the scheme, Whiddington arranged the two plates of the condenser P on vertical rods, as in Fig. 270. He found it was possible to detect the change in the distance x between the plates caused by hanging a milligramme weight at a distance of 5 inches along the lever attached to one of the rods. From previous experiments, in which the movements of the left-hand plate caused by known bending moments on the rod were measured with an accurate micrometer, it was ascertained that the alteration in x caused by the milligramme weight was of the order of only 4×10^{-9} inches.

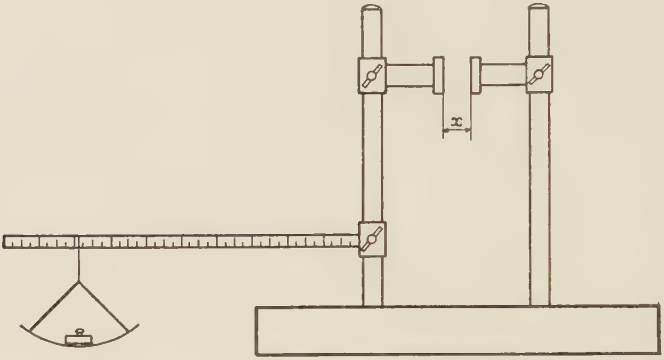


FIG. 270.

To measure comparatively large variations in x of the order of 10^{-5} inches, a rather simpler procedure was adopted. The note given out by the third circuit was first adjusted to the pitch of the heterodyne note. The alteration in x gave rise to considerable change in the pitch of the latter, but by adjusting the condenser C in the B circuit, it was possible to restore the note to its original pitch, using the standard note as a reference. Having calibrated the angular scale of the condenser in terms of measured variations in x, it made it possible to measure a variation by noting the corresponding point of adjustment of the condenser to restore the heterodyne note to its original pitch.

In connection with the latter method of using the scheme, Whiddington states that the frequency of the reference note given by the third circuit could be maintained constant to the order of 1 in 10^5 over a period of several hours.

It will be readily understood that an apparatus such as described above is extremely sensitive to even minute variations in capacity due to movements of neighbouring bodies, and for this reason has to be effectively screened by enclosing the various parts in metal-lined boxes.

The theory of the method as given by Whiddington * may be stated as follows :

The natural frequency, N, of a circuit comprising a capacity C connected to an inductance L is given by

$$N = \frac{1}{2\pi\sqrt{LC}}.$$

If the condenser is composed of two parallel plates of area A and separation x, we have

$$C = \frac{A}{4\pi x}.$$

Whence

$$N = \sqrt{\frac{x}{\pi LA}}.$$

Differentiating with regard to x, we get

$$\frac{dN}{dx} = \frac{1}{2\sqrt{\pi LAx}}$$

$$= \frac{N}{2x}.$$

The value of N is arranged to be of the order of 10^6, so that, assuming the plates are separated by 0·001 inch, we have

$$\frac{dN}{dx} = \frac{10^9}{2}.$$

Taking the least observable change in N as 1, the corresponding value for δx is 2×10^{-9} inches.

The fact that the least observable alteration in x from the

---

* *Phil. Mag.*, vol. xl. (Sixth Series), p. 634 (1920).

experiments was about twice this figure was attributed to the possibility of the plates not being so close as 0·001 inch, the value of x assumed in the calculation.

Dowling's "Ultra-micrometer."

The micrometer device used by Whiddington requires the use of at least two oscillatory circuits; the following scheme, due to J. J. Dowling, employs only one valve circuit. The scheme is shown diagrammatically in Fig. 271. The inductance L is included partly in the grid and partly in the anode circuits, the former portion having in parallel with it a variable, parallel-plate condenser C. With suitable adjustment of the condenser and of the tapping on the inductance, the circuit oscillates and gives rise to an increase in the anode current.

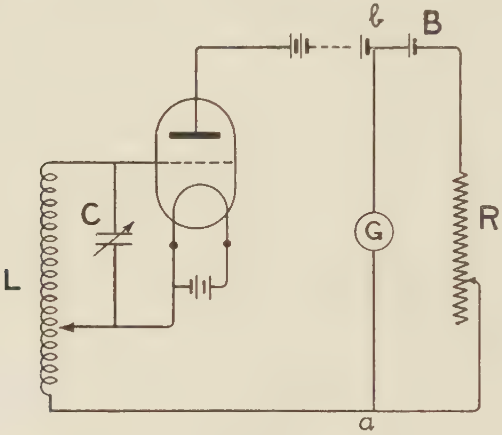


Fig. 271.

Alterations in the capacity of C produce corresponding variations in the anode current; by suitable choice of the values of L and C, it is possible to arrange for the current to vary in a linear manner with small changes in the distance separating the two parallel plates of the air condenser C.

Under the usual working conditions and with a condenser consisting of a pair of 10-cm. circular plates spaced 0·025 cm. apart, an alteration of 10^{-4} cm. in the spacing is accompanied by a variation of 8 microamperes in the anode current. Since the average current is of the order of 3 milliamperes, this variation could not be detected by a milliammeter, but can readily be made observable by arranging a galvanometer, as shown in Fig. 271. The galvanometer G is shunted by a resistance R having in series with it a battery B. The value of R is adjusted so that the drop in potential between the points a and b, corresponding to a certain value of anode current flowing through R, is exactly counterbalanced by the E.M.F. of the battery B. With the points a and b at the same potential, the current passing through the galvanometer is zero. This state of balance is, however, immediately upset when a change occurs in the anode current. If the change is denoted by δi and the resistance of the galvanometer by g, it can readily be shown that the resulting galvanometer current will be equal to

$$\frac{\mathrm{R}}{\mathrm{R}+g}\,.\,\delta i.$$

By making R large as compared with g, practically the whole of the variation of the anode current can be made to pass through the galvanometer. Thus, by using only a moderately sensitive galvanometer giving a deflection of, say, 100 scale divisions per microampere, the alteration of 10^{-4} cm. in the separation of the condenser plates, referred to above, would result in a deflection of 800 divisions. One scale division would, therefore, indicate a movement of one eight-millionth of a cm. (about one twenty-millionth part of an inch).

As a test of the extraordinary sensitivity of the method, Dowling made an experiment involving the compression which occurs over a 5-cm. length of a vertical steel rod, 12 mm. diameter, when loaded axially. The method of test will be gathered from Fig. 272. The two steel condenser plates were attached to the rod at points 5 cm. apart, being supported by adjusting screws and springs from ebonite rings. It was found that for a certain arrangement of the electrical circuit,* increments of 0·5 kilogramme to the axial load on the rod produced deflections of the galvanometer of as much as 80 divisions. The calculated compression of the rod for this load was $1{\cdot}08 \times 10^{-6}$ cm. (approximately half a millionth of an inch).

This high degree of sensitivity was obtained without having to resort to shielding of the apparatus from outside electrical disturbances. Higher sensitivity is possible, provided suitable precautions are taken to maintain constancy throughout the various parts of the apparatus during the experiments. Particular attention has to be paid to the small battery in the galvanometer circuit, and even slight fluctuations in room temperature have to be carefully avoided.

In his description of this electrical method of measuring small displacements,* Dowling refers to several applications involving accurate measurements. These include a refined extensometer for both longitudinal and lateral strains, a method for studying plant growth, the measurement of very small changes in fluid pressure by recording the minute variations in the flexure of the diaphragm of a pressure gauge, an indicator for a sensitive spring balance, a method of determining the constant of gravitation and a recording mechanism in connection with a seismometer.

---

* About ten times as sensitive as that mentioned above.

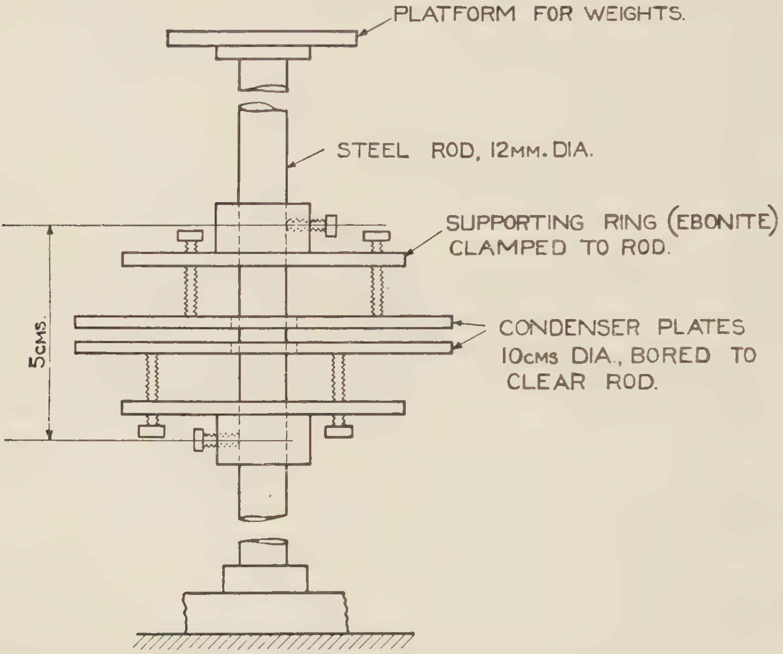

PLATFORM FOR WEIGHTS.
STEEL ROD, 12MM. DIA.
SUPPORTING RING (EBONITE) CLAMPED TO ROD.
CONDENSER PLATES 10CMS DIA., BORED TO CLEAR ROD.
5CMS.

Fig. 272.

Thomas' Method of Measuring Small Displacements.

A diagrammatic arrangement of the valve circuit used by H. A. Thomas of the National Physical Laboratory for measuring small displacements is shown in Fig. 273. It consists essentially of a Hartley oscillating circuit, in which variations in anode current are produced by movements of a metal plate P in the field of the inductance L. The eddy currents induced in this plate absorb energy from the circuit, and it will readily be understood that the effect upon the anode current depends upon the distance of the plate P from the inductance. Under suitable conditions, it is possible to arrange for the anode current to vary in a linear manner with respect to movements of the plate over a range of about 0·01 inch, the sensitivity of measurement being of the order of 10^{-8} inch.

---

* *Phil. Mag.*, vol. 46, p. 81 (1923).

The variations in anode current are measured with a galvanometer, using the "zero shunt" method described in connection with the Dowling scheme.

In practice, the inductance L, consisting of about 100 turns of No. 30 I.W.G. insulated copper wire wound on an 1½-inch ebonite bobbin, is brought near to the body whose displacements are to be observed. Since the latter is usually of metal, its displacements are recorded, just as in the case of the plate P, by deflections of the galvanometer, without the necessity of making any attachments to it. This is important from the point of view of avoiding any risk of affecting the free motion of the body, especially in the case of rapid vibratory motions.

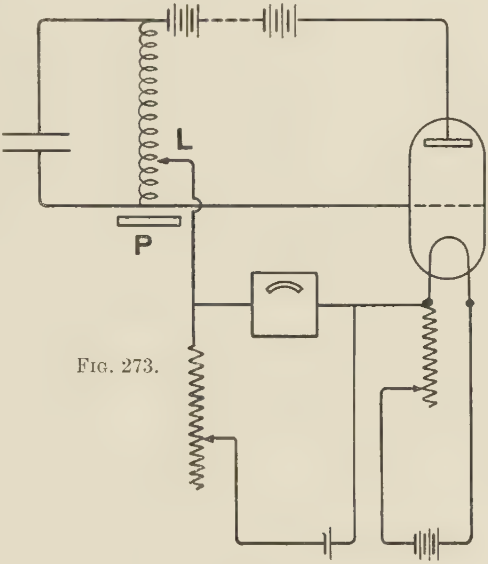


Fig. 273.

A D'Arsonval galvanometer is used for measuring single displacements, or slow movements, whilst movements of a vibratory character having frequencies as high as 600 per second can be dealt with by using an Einthovan string galvanometer.

When set up for any particular purpose, the apparatus is calibrated by moving either the coil or the plate through convenient known distances by means of a micrometer.

The method has been put to such a practical application as the measurement of rapidly varying strains in bridge members due to live loads.* The observations can be recorded at any convenient distance from the attachments to the bridge members by suitable extension of the galvanometer leads.

---

* See *Report of Bridge Stress Comm.* p. 193 (H.M.S.O., 1928).

Electric Telemeters.

During recent years an investigation was carried out at the Washington Bureau of Standards by O. S. Peters and R. S. Johnston with the view of perfecting an extensometer, the principle of which is based upon the change which occurs in the electrical resistance of a pile of carbon plates when subjected to variations in pressure, or, what is virtually the same thing, to variations in its overall dimension. Difficulties arising from hysteresis effects and non-linear relationship between the resistance and displacement have been overcome, and a satisfactory solution to the problem obtained.

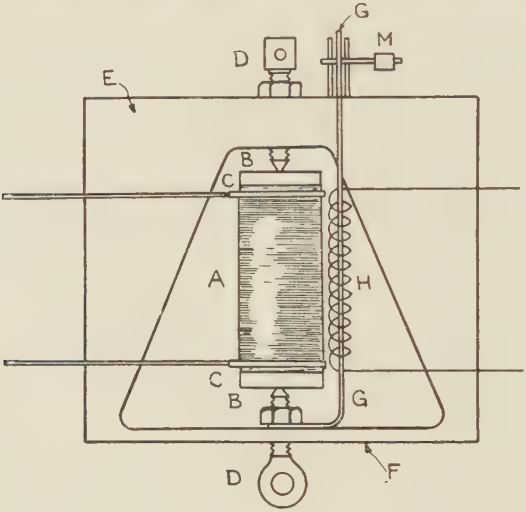


Fig. 274.

One method adopted for mounting the pile of carbon plates is shown in Fig. 274. The plates A, about 50 in number and in the form of annular rings, are enclosed between steel end-plates B with mica insulating discs C inserted at the ends. The end-plates are clamped centrally between a pair of set-screws D, tapped into the top and bottom of a steel block E, having its central portion cut away as shown. The relatively thin base F of the block acts as a spring, which, by suitable adjustment of the set-screws, can be made to hold the pile of plates together under any desired initial pressure. The small displacement to be measured is communicated to this spring, the variation in flexure of which causes a corresponding change of pressure on the carbon plates, and so alters their resistance.

The instrument is calibrated by measuring the deflection of the spring in terms of the angle of rotation of a small mirror M, attached to a roller which is clipped between supports on the top of the block and a rod G attached to the spring. The coil H serves to magnetize the rod G, and prevents slipping of the roller.

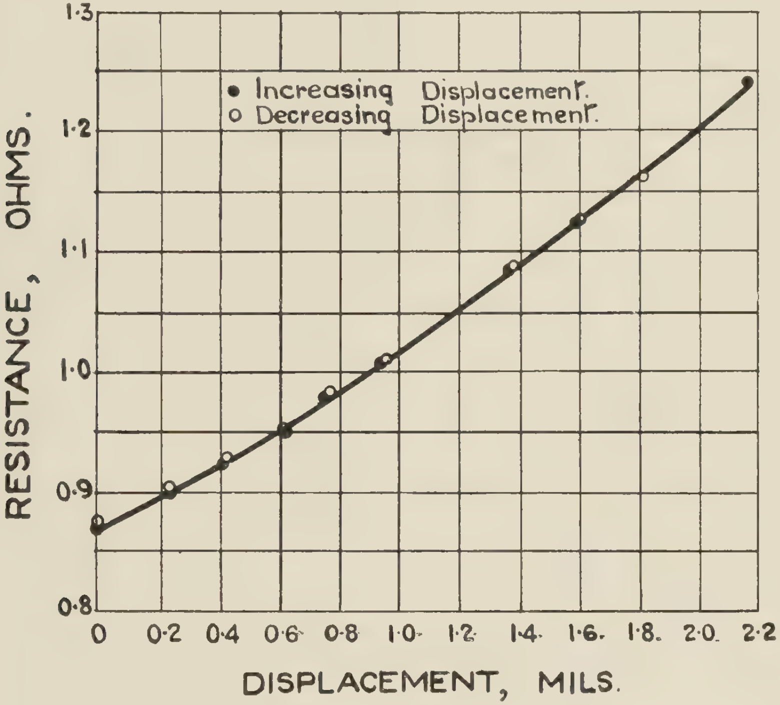


Fig. 275.

The type of displacement-resistance curve given by such an arrangement of carbon plates is shown in Fig. 275, from which it will be noted that a displacement of only about 0·002 inch gives rise to a change of nearly 40 per cent. in the resistance of the pile. Freedom from hysteresis is shown by the close agreement between increasing and decreasing values on the curve, which, it is to be noted, is not a straight line. By utilizing a pair of similar resistors, and so arranging them that the displacement causes an increase in the resistance of one and a decrease in the other, it is possible to obtain a linear relationship between the displacement and the combined effect upon the two resistors.

To accomplish this, the two piles of plates are inserted in two arms of a Wheatstone bridge circuit, as shown in Fig. 276. The other two arms consist of suitable fixed resistances R_1 and R_2 and the two parts of an adjustable resistance R_3, with which the bridge can be balanced initially. Any alteration in the resistances of the carbon plates disturbs the balance and gives rise to a deflection of the galvanometer connected between the junction point of the two resistors and the movable contact of the adjustable resistance R_3. It can readily be shown that, provided the galvanometer current is small compared with the main current in the circuit, its values are proportional to the combined changes in the resistance of the two carbon piles and, therefore, to the displacement applied to them.

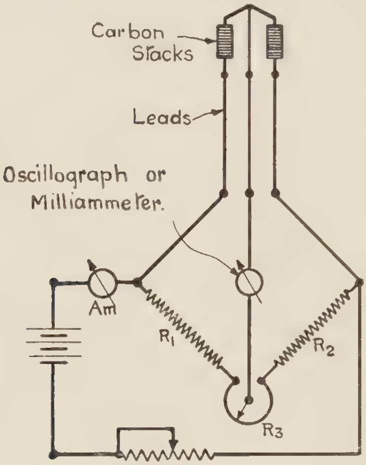


Fig. 276.

As an actual example of the sensitivity of a pair of resistors incorporated in an extensometer, it may be mentioned that a displacement of 0·012 inch gave rise to a current of about 50 milliamperes across the bridge circuit.

A type of extensometer which has been successfully applied to the measurement of strains in structural members is shown diagrammatically in Fig. 277. The steel block A is recessed in the middle, leaving a flexible tongue B, the free end of which is connected to a rod C guided in the tube D. The other end of the rod makes contact with another rod E, provided with a screw adjustment in a smaller block F. The two blocks A and F are clamped to the structural member to be tested, the sharp steel gauge-points being pressed into the metal. Alteration in the length of the member between the gauge-points, due to applied loads, causes a flexure of the tongue B, which gives rise to equal and opposite displacements of the inner ends of two carbon-plate resistors G_1 and G_2. The resultant changes in their resistances produce a current across the bridge circuit in which they are connected. This current is measured by a suitable galvanometer or milliammeter, and is directly proportional to the strain in the member under observation.

It is claimed that, under good conditions, measurements of strains by this method can be relied on to 0·5 per cent, whilst ordinary working conditions should not increase the uncertainty to more than 2 per cent.

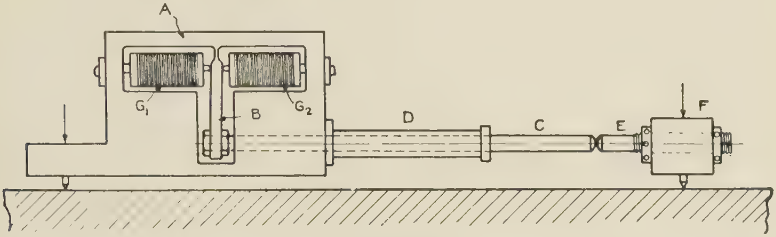


Fig. 277.

By connecting the leads from a number of such extensometers to a central recording instrument, it is possible for one observer, by suitable switching arrangements, to record the strains in several members of a structure.

Strains of an oscillatory character can be dealt with equally well by the use of an oscillograph or an Einthovan galvanometer as the current measuring instrument.

ADDITIONAL REFERENCES FOR CHAPTER XII

"Sensitive Measuring Apparatus," R. Whiddington, *Machinery*, vol. 18, p. 752 (1921).

"The Ultramicrometer," R. Whiddington, *Engineering*, vol. 114, p. 391 (1922); vol. 110, p. 384 (1920).

"Recording Ultramicrometer," J. J. Dowling, *Engineering*, vol. 112, p. 395 (1921).

"Measurement of Mechanical Vibration," H. A. Thomas, *The Engineer*, vol. 139, p. 102 (1925).

"Precision Measurement of Small Motions of Solid Bodies," H. A. Thomas, *The Engineer*, vol. 135, p. 138 (1923).

"Some Simple Experiments with Thermionic Valves," E. H. Rayner, *Engineering*, vol. 121, p. 603 (1926).

"Application of Oscillating Valve Circuits to the Precise Measurement of Certain Physical Quantities," J. Wagstaff, *Phil. Mag.*, vol. 47, p. 66 (1924).

"Electric Telemeters," O. S. Peters and R. S. Johnston, *Engineering*, vol. 116, p. 252 (1923); *Proc. Amer. Soc. for Testing Materials*, vol. 23, pt. ii., p. 592 (1923); vol. 27, pt. ii., p. 522 (1927).

"A New Relay for Morse Reading," *Wireless World*, vol. 20, p. 262 (1927). (Mohn's use of a special neon tube; device could be made to serve as a contact indicator.)

"A Distant Reading Instrument for the Measurement of Small Displacements," E. F. Relf and L. F. G. Simmons, *Phil. Mag.*, vol. 4, p. 269 (1927).

"The Ultramicrometer," J. Obata, *Jour. Opt. Soc. of Amer.*, vol. 16, p. 419 (1928).

"Application of the Whiddington Ultramicrometer," H. Lloyd, *Jour. Sci. Insts.* vol. 6, p. 81 (1929).

CHAPTER XIII

MEASUREMENT OF FINE WIRES AND FIBRES

THE accurate measurement of the diameters of fine wires such as are used for the filaments of electric lamps and valves is a subject which is of interest both from scientific and commercial points of view.

It is obvious at the outset that, when dealing with wire having a diameter of only one or two thousandths of an inch, or even less, ordinary mechanical methods cannot be used, owing to the risk of compressing the wire during the measuring operation. This danger can be avoided by optical methods, in which the measurements are carried out either under a fairly high power microscope or at the screen of a projection apparatus,* but the accuracy obtainable is rather limited. Moreover, with very fine wires, difficulty arises in obtaining satisfactory definition owing to diffraction effects, and other means have to be employed when high accuracy is required.

Eden's Method.

The following scheme, which was brought to the notice of the writer some years ago by E. M. Eden, is worthy of attention as being applicable where a short sample of the wire can be cut off for purposes of measurement. The sample is clamped horizontally

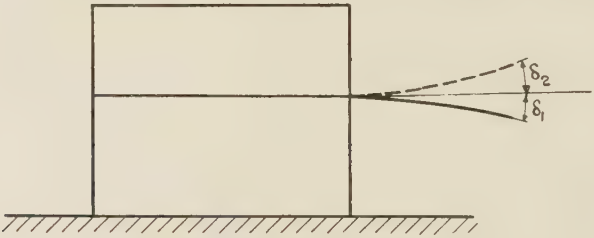


FIG. 278.

---

* For description of the "Lewbeck" apparatus, see p. 236.

at one end between two metal blocks, from which it projects in the form of a cantilever, as in Fig. 278. The combined block is afterwards " spot ground " on the top and bottom faces so as to render them parallel.

Placing the block on a surface plate, the difference in height δ_1 between the two ends of the wire is measured by means of a micrometer microscope mounted horizontally on a base resting upon the same surface plate. The block is then inverted and a similar measurement δ_2 is taken. The mean of δ_1 and δ_2 gives the true dip of the wire, independent of any permanent lack of straightness.

The diameter of the wire can then be obtained from the usual formula for a cantilever,

$$\tfrac{1}{2}(\delta_1+\delta_2)=\frac{wl^4}{8\mathrm{EI}},$$

where w = weight of wire per unit length.
l = projecting length of wire.
E = modulus of elasticity.
$\mathrm{I}=\dfrac{\pi d^4}{64}$.
d = diameter of wire.

Tomlinson's Methods.

(i) *Mechanical Lever.*—The following method was devised by G. A. Tomlinson at the National Physical Laboratory in 1925, for accurately measuring the diameters of fine metal wires.

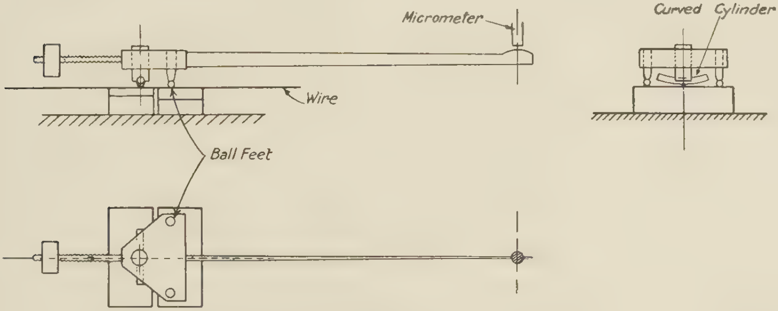


FIG. 279.

The apparatus consists essentially of a light lever, Fig. 279, having two ball-feet resting upon a pile of block gauges wrung down on to a surface plate. The underside of the short arm of the lever has attached to it transversely a small, lapped steel cylinder which is bent very slightly in a vertical plane. The wire to be measured is placed parallel to the lever, and between the lowest part of the small cylinder and a second pile of block gauges as shown. A reading is then taken with a vertical micrometer head by sighting contact with the edge of a thin sector at the opposite end of the lever. Having removed the wire, the pile of block gauges beneath the cylinder is increased by a definite amount equal to the approximate size of the wire, and a further micrometer reading is taken. All that is then required to obtain the diameter of the wire is the magnification of the lever. This is found by noting the alterations in the micrometer reading corresponding to known changes in the size of the block gauges supporting the cylinder.

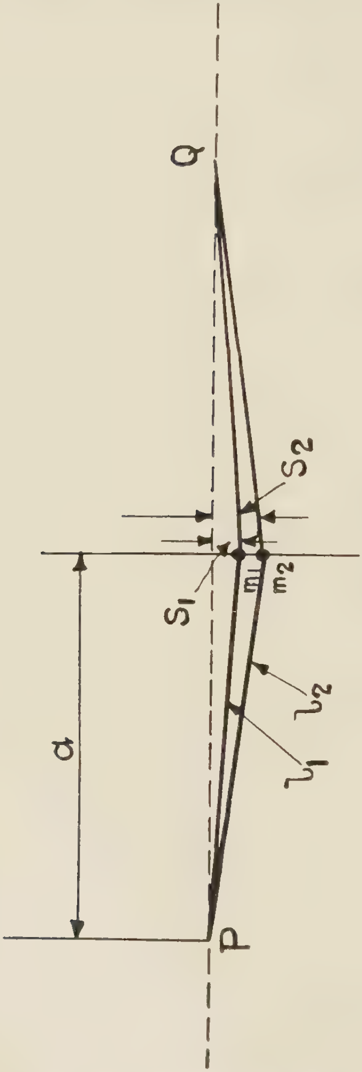


Fig. 280.

This method is capable of an accuracy of 0·00001 inch, or so.

The pressure on the wire during the measurement can be reduced to a negligible amount by suitable adjustment of the counterbalance weight at the left-hand end of the lever.

It should be mentioned that the curvature of the small steel cylinder is so slight that the setting of the wire under the centre point can be carried out to a sufficient accuracy by eye.

Variations in the diameter of the wire, either along its length or round it, can be readily investigated by this method.

(ii) *Measurement of Quartz Fibres by Elastic Straining.* –Another ingenious method was devised by Tomlinson in 1927, for dealing with fine quartz suspension fibres having diameters as small as 0·00002 inch. The scheme can also be used for fine metal filaments.

When suspending a galvanometer mirror, it is very desirable at the outset to be in a position to select a quartz fibre of the required stiffness to give a satisfactory period of oscillation to the system. The method about to be described has the additional advantage that it enables an accurate measurement to be made of the diameter of quartz fibres whilst still mounted on the frames on which they are usually wound and stored after being made.*

The frame is placed in front of the lens of a horizontal projection apparatus (such as is described on p. 229) with the fibre approximately horizontal, so that an image of the fibre magnified fifty times is thrown on to the screen of the apparatus. A small wire rider, having a mass of one or two milligrammes, is placed on the fibre towards the centre of its span, causing it to deflect as in Fig. 280. The amount of deflection, S, at the point of application of the rider is measured at the screen over a definite span, PQ, which, for convenience, may be taken as a metre. Similar measurements are made with a second rider of different mass.

From these measurements, the average area, A, of the cross-section of the fibre may be derived as follows:

Let T = tension in the fibre.
$2l$ = length of fibre between P and Q.
2L = total length of fibre between the supports at its extremities.
E = modulus of elasticity of fibre ($=5{\cdot}18\times10^{11}$ dynes per sq. cm. for quartz fibre).
$2a$ = PQ = 1000 mm.
S = deflection at centre over span $2a$.
m = mass of rider.

Then, neglecting the weight of the fibre itself,

$$\left.\begin{aligned} \mathrm{T}_1 &= \frac{l_1 m_1 g}{2\mathrm{S}_1}, \\ \text{and} \qquad \mathrm{T}_2 &= \frac{l_2 m_2 g}{2\mathrm{S}_2}. \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

From similar triangles, $\frac{\mathrm{L}_1}{\mathrm{L}_2}=\frac{l_1}{l_2}$, and from the definition of the modulus E,

---

* For method of producing fine quartz fibres, see Watson's *Practical Physics*, (1913 Edition), p. 581.

$$\frac{T_2 - T_1}{AE} = \frac{L_2 - L_1}{L_1} = \frac{l_2 - l_1}{l_1}. \quad . \quad . \quad . \quad . \qquad (2)$$

Substituting the values of T_1 and T_2, from (1) we have

$$\frac{g}{2AE}\left(\frac{l_2 m_2}{S_2} - \frac{l_1 m_1}{S_1}\right) = \frac{\sqrt{a^2 + S_2^2} - \sqrt{a^2 + S_1^2}}{l_1}.$$

In this equation, a may be substituted for l_1 and l_2 without appreciable error, in which case we may rewrite it as

$$\frac{ag}{2AE}\left(\frac{m_2}{S_2} - \frac{m_1}{S_1}\right) = \frac{\sqrt{a^2 + S_2^2} - \sqrt{a^2 + S_1^2}}{a} = \frac{S_2^2 - S_1^2}{2a^2}$$

approximately, since S_1 and S_2 are small compared with a.

Hence $$A = \frac{a^3 g}{E}\left(\frac{m_2}{S_2} - \frac{m_1}{S_1}\right)\frac{1}{S_2^2 - S_1^2}.$$

The following table gives the results of experiments made with six fibres :

Fibre No.	m_1 gm.	m_2 gm.	S_1 mm.	S_2 mm.	T_1 dynes.	T_2 dynes.	Fibre diameter, microns.
1	0·00072	0·00178	20·0	27·7	8·8	15·8	1·51
2	0·00106	0·00394	28·2	32·1	9·2	30·0	3·30
3	0·00054	0·00126	30·0	43·3	4·4	7·1	0·59
4	0·00106	0·00250	24·6	34·1	10·5	18·0	1·28
5	0·00106	0·00250	21·6	27·2	12·0	22·5	2·17
6	0·00106	0·00250	20·3	31·7	12·8	19·3	1·16

It will be noted that the masses of the small wire riders used varied from about $\frac{1}{2}$ to 4 mg. Calculations showed that the actual tensile stresses set up in the fibres were far short of the ultimate strength of quartz.

That one is justified in neglecting the weight of the fibres in comparison with that of the riders, when deducing the above formula, is readily seen when it is stated that a quartz fibre one micron in diameter, for example, has a weight of only $1{\cdot}73 \times 10^{-8}$ gr. per cm.

It has to be remembered, of course, that the diameter as found by this method is an average for the whole length of fibre under tension.

Optical Diffraction Method for Measuring Quartz Fibres.

A second method for determining the diameter of quartz fibres was developed by H. Barrell, and is based upon the brilliant colour effects which are seen when such fibres are illuminated by a beam of white light. The colours, which are due to diffraction effects, are best seen in a beam of parallel light from an arc lamp, as in Fig. 281. The light from a lamp A is collimated by a lens L, and falls upon the fibre, the section of which is shown at F. Viewed from a position such as E, the fibre then appears brilliantly coloured. Upon varying the angle θ, the colour is found to change continuously through one spectrum after another, gradually becoming fainter as θ increases.

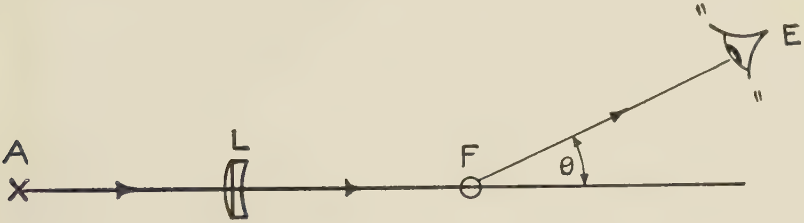


FIG. 281.

The effect is similar to that which occurs when a fine slit is illuminated by a beam of white light.[*] Here a known relationship exists between the width of the slit, the angle θ and the wave-length of the light transmitted in the direction θ. Using this same relationship in the case of the fibres, values were found for their equivalent "slit-widths" which agreed reasonably well with the diameters determined by Tomlinson's method.

A fuller account of the two methods will be found in *Jour. of Sci. Insts.* vol. iv. p. 410 (1927).

Cambridge Instrument Co.'s Fibre Measuring Machine.

The Cambridge Instrument Company has recently constructed an apparatus for measuring the diameters of quartz fibres and fine wires below a size of about 0·02 mm. A diagrammatic arrangement of the instrument is shown in Fig. 282,[†] from which it will be observed that in several features it resembles Eden's Slip Gauge Comparator.[‡]

---

[*] See Schuster's *Theory of Optics*, 2nd ed. p. 103, or Wood's *Physical Optics*, 2nd ed. p. 201.

[†] Reproduced from *Engineering* by courtesy of the Editor.

[‡] See Vol. I. p. 241.

Each of the measuring jaws, A and B, is capable of slight to-and-fro movement on a pair of thin, steel strips C. To insert a fibre for measurement, the jaw B is displaced to the right by operating a cam D. On releasing the latter, the jaw springs back until it rests against an abutment screw E. The fibre is thereby clipped between the measuring faces, and the other jaw, A, is displaced to the left away from its abutment F. This displacement is amplified at the end of a light pointer G, mounted on two parallel steel strips, one of which is fastened to the rear end of the jaw, and the other to a rigid block integral with the base of the instrument.

Deflection of the pointer breaks contact between its tip and a small arm H, fastened to a light helical spring at a short distance from its fixed end. This separation is indicated electrically by a galvanometer, connected as shown. The other end of the spring is soldered to a fine metal strip J, which is wrapped round the cylindrical axle of a pointer. To obtain a measurement of the fibre, the spring is extended by turning the pointer until electrical contact is restored at H. The reading of the pointer is then noted against a circular scale.

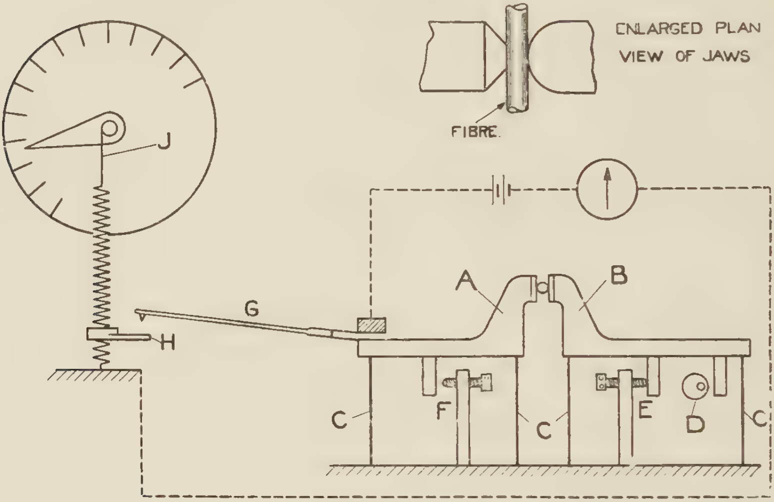


FIG. 282.

The total magnification is such that a difference of 1 micron in the diameter of a fibre is recorded as a displacement of 14 mm. round the periphery of the dial—an amplification of 14,000 times. It is stated that repetition of reading can be obtained to a tenth of a micron.

The scale of the instrument is calibrated by taking a series of readings on a number of quartz fibres, for the diameters of which the makers rely upon optical projection to a high magnification.*

One of the measuring faces of the instrument is flat, and the other in the form of a cylinder with its axis vertical, as shown in the enlarged view. These faces project through an aperture in a glass plate which covers the apparatus. To avoid the effect of error in parallelism between the faces, the fibres are always located between them at the same position, by placing them across small horizontal rods resting on the cover. Elastic deformation of the fibres at the measuring contacts is reduced to a minimum by restricting the pressure between the jaws to 10 milligrams, or so.

It should be mentioned that, in the actual instrument, the pointer G is arranged so that its deflections occur in a horizontal plane. The helical spring is also horizontal.

---

* In view of the diffraction effects which occur when projecting such fine fibres, and the fact that, owing to their transparency, they behave like cylindrical lenses, it is questionable whether this method of measuring the standardizing fibres gives a true value of their diameters.

ADDITIONAL REFERENCES FOR CHAPTER XIII

"Micrometer for Measuring Diameter of Quartz Fibres," *Eng.*, vol. 125, p. 655 (1928).

"Mikrotast-Feindrahtmesser," M. Bartholdy, *Zeit. für Feinmech. und Präzision*, vol. 35, p. 250 (1927).

"Ein optisches Mikrometer," I. Runge, *Zeit. für tech. Phy.*, No. 12, p. 484 (1928).

"Wire of Very Small Diameter," *Amer. Mach.*, vol. 67, p. 987 (1927-28).

CHAPTER XIV

NOTES ON DESIGN OF MEASURING INSTRUMENTS

The very noticeable improvement which has taken place during the last decade or so in the accuracy of mechanical measurements may be attributed, in a large measure, to a better appreciation of the fundamental principles underlying the correct design of measuring instruments. This particular branch of design has received full consideration in recent discourses by such able exponents as Sir Horace Darwin,* Professor A. F. C. Pollard,† J. E. Sears ‡ and R. S. Whipple,§ and all that can be attempted here is to give a few examples showing how the application of correct principles in design has enabled instrument makers to overcome many of the difficulties and sources of error which so frequently arise in connection with accurate measurements.

In the descriptions of measuring machines to be found in various parts of this book, attention has already been drawn on occasions to special points in the designs which have a direct influence upon the accuracy attainable from the instruments. It is felt, however, that the importance of the subject, and the desirability of treating it under a single heading, justify further reference to some of the more important of these points in the present chapter.

Geometric Location.

In designing measuring instruments, it is frequently required to locate two parts in relation to one another in such a manner that there is no " play " between them, and so that it is possible, after separation, to bring them together again in exactly the same relative positions.|| The problem is readily solved by providing one of the

---

* *Dict. of Applied Physics*, vol. iii. pp. 445-50.

† Royal Soc. of Arts, Cantor Lectures, 1922.

‡ *Dict. of Applied Physics*, vol. iii. pp. 621-30.

§ *Engineering*, vol. 41, p. 659 (1921).

|| Maxwell. See *Handbook to Loan Collection of Scientific Apparatus* (1876).

parts with three rounded feet, which are located on the other part either by a conical hole, a vee slot and a plane, or by three vee slots, as in Fig. 283, A and B respectively. In each case the upper body is definitely located, and since the constraints are just sufficient in number to achieve that object, the forces on the body are equally definite. It should be mentioned that the axis of the single vee groove should be collinear with the centre of the conical hole, and, in the alternative arrangement, the axes of the three grooves should intersect at a common centre. This being so, it is possible for the distance between the three rounded feet or between the locating points on the base to vary (due, for example, to temperature changes) without introducing undesirable forces in either of the two members.

Realising that a body free to move in space has six degrees of freedom, three of translation along mutually perpendicular axes, and three of rotation about each of the same axes, there is no difficulty in understanding how each of the arrangements in Fig. 283 results in definite location—*i.e.* complete loss of freedom—of the upper body upon the lower one. It is clear that, without the vee grooves or hole, the upper body could slide about upon the lower one, and would then possess three degrees of freedom, two of translation and one of rotation.

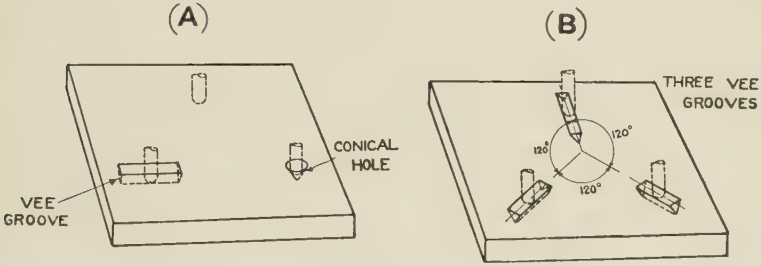


FIG. 283.

Locating one foot in the conical hole (Diagram A) does away with the possibility of translation, but still leaves the body free to rotate about that foot. With a second foot located in the vee groove, this last remaining freedom of motion is prevented and the body becomes fixed with respect to the base plate.

In the second arrangement, suppose one of the grooves be eliminated, the body will then be free to rotate about a virtual centre in line with that groove. The presence of the third groove prevents this rotation, and thus destroys the last degree of freedom.

Geometric Slides.

If we wish the upper body to be capable of sliding over the lower one along a straight path, the necessary freedom of translation can be provided in the arrangement A, Fig. 283, by replacing the vee groove and conical hole by a long vee groove to accommodate two of the feet.

The accuracy of the motion will depend, of course, upon the straightness and uniformity of the vee groove and the parallelism between its axis and the plane surface supporting the third foot.

One method of obtaining a high degree of accuracy by simple machining operations is to use the arrangement shown in Fig. 284.

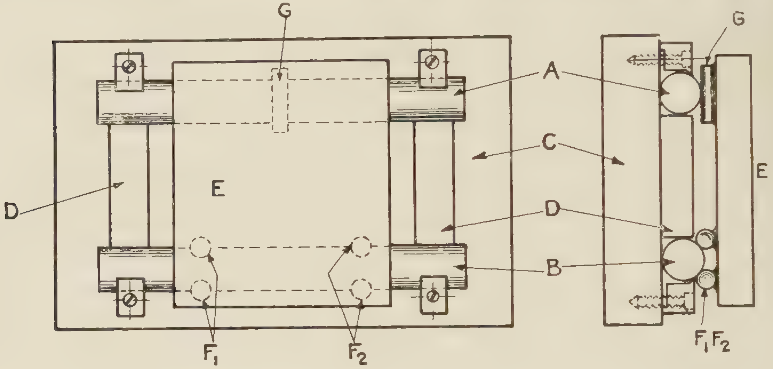


Fig. 284.

The "guides" consist of two hardened steel cylindrical rods, A and B, resting on the ground surface of a base plate C. These rods need not necessarily be of equal diameter, but they should be accurately parallel and straight, conditions which are readily attained by cylindrical grinding followed, if extreme accuracy is desired, by lapping. The rods are suitably clamped down, or soldered to the flat base with two equal distance pieces D interposed between their ends. The carriage E, which slides along these two ways, has fixed to its underside two pairs of hardened steel balls, F_1, F_2 and a short cylinder, G. The latter rests across one of the rods, whilst the balls serve to locate the carriage on the other. It will be noted that there are five points of contact between the base and the carriage. The latter is therefore definitely located, except as regards freedom to slide along the bars. If desired, the carriage can be lifted off the guides and replaced with the certainty of following its former path. The use of hardened steel for the guide rods, balls and the cylinder G, enables the initial accuracy of the motion to be prolonged almost indefinitely, but should the guide rods become worn locally, it is a simple matter to restore the accuracy by turning them slightly on the base plate.

It frequently happens in designing measuring machines, that the effort required to move such a carriage has to be reduced to a minimum. For this purpose the sliding motion of the carriage can be replaced by rolling on steel balls located in suitable guides. The usual arrangement is shown in Fig. 285, where it will be noted that the carriage A is supported on three balls resting in a pair of vee-grooves cut in the base plate B. Proper location of the carriage is ensured by a single vee-groove C, in the underside of it, and so situated as to be above the groove in the base containing the two balls. A flat surface on the base of the carriage rests upon the remaining ball in the other vee-groove.

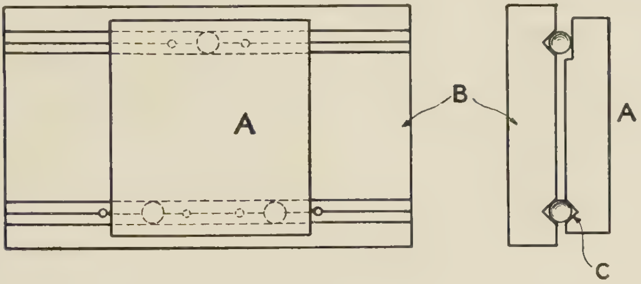


Fig. 285.

The travel of the balls is limited by pins fixed in the lower vee-grooves.

In order to avoid trouble from the balls sinking into small pit-holes in the guiding surfaces, it is usual to duplicate each of the three balls.

In practice, the base and carriage are usually of cast-iron, and it is found that the guiding surfaces soon begin to show the tracks of the hardened steel balls, which tend to bed themselves into the surfaces. Should the tracks become worn unevenly, the accuracy of the motion of the carriage suffers accordingly. This risk can be avoided by forming slight tracks in the guiding surfaces by lapping them with a short length of rod of the same diameter as the balls. Incidentally, this process affords an opportunity of rectifying any errors in straightness in the machining of the guiding surfaces.

It should be pointed out, however, that the alteration from point contact between the balls and the guides to contact along a short line, whether it is produced by wear or initial lapping, introduces a certain amount of rubbing, and therefore friction, at the contacts.

The method of forming the guides patented by A. C. Wickman and used in his measuring machine,* not only obviates wear, and therefore friction, by using hardened steel guides, but also affords a ready means of obtaining a high degree of accuracy in the straightness of the motion of the carriage.

The three vee-groove guides are replaced by corresponding pairs of hardened steel rods, A, B and C, Fig. 286, each pair of rods being located in a rectangular recess with accurately parallel sides. The rods are ground and lapped and are carefully tested for straightness.

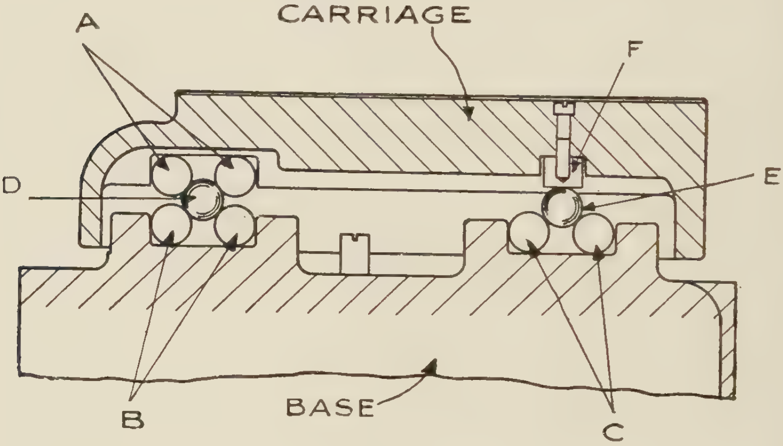


Fig. 286.

The flat supporting surface on the carriage consists of a hardened steel strip F, attached to its underside.

The carriage runs, as usual, on steel balls, D and E. It will be noted that the weight of the carriage serves to press the rods into contact with the sides of the recesses. One advantage of this arrangement is that the truth of the "ways" can be readily checked by simple measurements over the rods.

The freedom of motion obtained with hardened steel balls rolling between such hardened guides can be judged from the fact that, in the Wickman measuring machine, the carriage, which weighs about 75 lbs., can be started from rest by a force of less than two ounces.

---

* See Vol. I. p. 285.

The Principle of Alignment.

The majority of instruments and machines used in engineering practice for measurements of length are based on the same general principle. The distance to be determined is traversed by a slide or other movable member, the displacement of which is measured with a micrometer screw, scale or some other standard of reference.

It is clear that the accuracy of the measurement depends to a large extent upon that of the reference standard, but it is not generally appreciated that another important factor which affects the accuracy is the position of the measuring point with respect to the axis of measurement. In Fig. 287, for example, the measurement, M, of the movement of a slider from one position A to another A¹ along a bed B, does not give necessarily the distance traversed by all points on the slider. Should the bed be bent, as shown in the diagram, it is evident that the distance L, traversed by a point such as P, will be greater than the measurement M by an amount equal to $h \,.\, \delta a$, where h is the distance from P to the line of measurement and δa the small angle of tilt experienced by the slider in passing from A to A¹. Only when the bed is perfectly straight, or when the measuring point P lies along the axis of measurement, does the error vanish. Even slight departures from straightness in the bed are sufficient to produce appreciable errors when the offset h of the measuring point amounts to several inches.

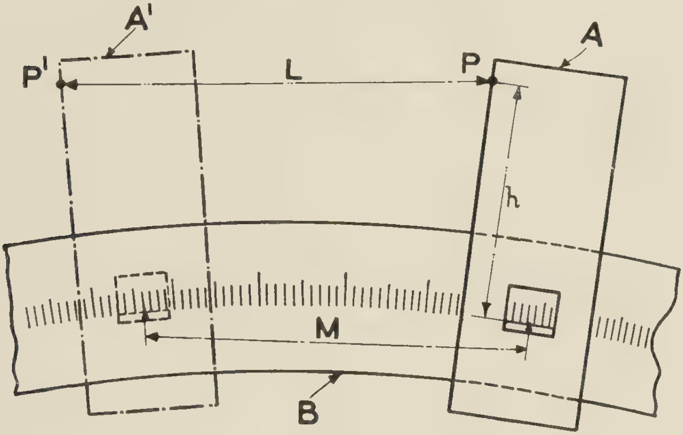


FIG. 287.

For example, suppose the bed takes the form of an arc of a circle which departs from a straight line by only 0·0001 inch at the centre of a 10-inch traverse. The angle of tilt of the slide would then amount to 1/12500 of a radian (about 16 seconds of arc), and with h equal to, say, 5 inches, the discrepancy between the measurement M and the distance traversed by the point under consideration would be as much as 0·0004 inch.

It is evident therefore that, failing a high degree of accuracy in the straightness of the slides, it is important, where fine measurements are concerned, that the line of measurement should pass as closely as possible through the point whose displacements are desired. For example, in the case of a travelling microscope, the axis of the micrometer screw should be arranged to pass through the focal point.

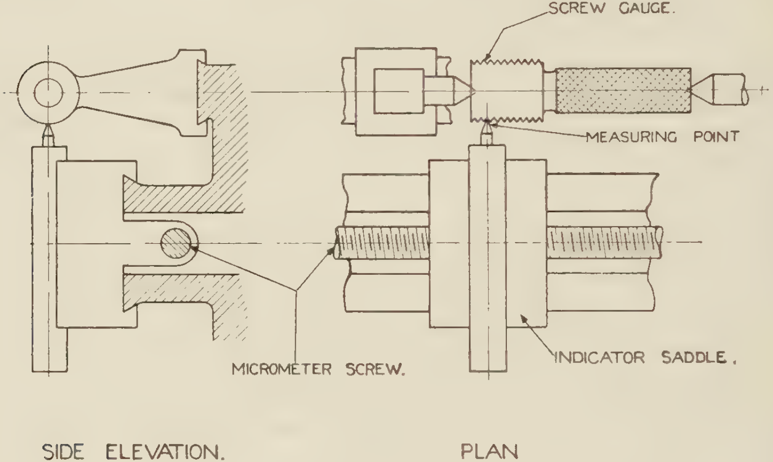


FIG. 288.

A typical example of the effect of lack of alignment between the path of the measuring point and the axis of measurement occurs in an early design of screw-pitch measuring machine, a portion of which is shown diagrammatically in Fig. 288. The measuring point in this machine was not only as much as 5 inches or so away from the axis of the micrometer screw, but this distance also varied according to the size and kind of the screw being tested, being situated on one side of the centres when measuring plugs and on the other when measuring ring screws. Any lack of straightness of the bed of the machine would thus have a variable effect upon the actual traverse of the measuring point depending upon the size and type of screw being tested.

The results of three separate calibrations of the machine with the measuring point set first an inch in front of the centres, then along the line of centres, and finally an inch behind them, are shown in

Fig. 289. The three curves show substantial differences, and clearly indicate that the error in the movement of the measuring point increases with its distance from the axis of the micrometer screw.

It should perhaps be mentioned that adherence to the principle of alignment often leads to some sacrifice of simplicity in design, thereby adding to the cost of construction of an instrument. It may generally be taken, however, that where accuracy is really essential, the principle should be adopted in spite of these considerations.

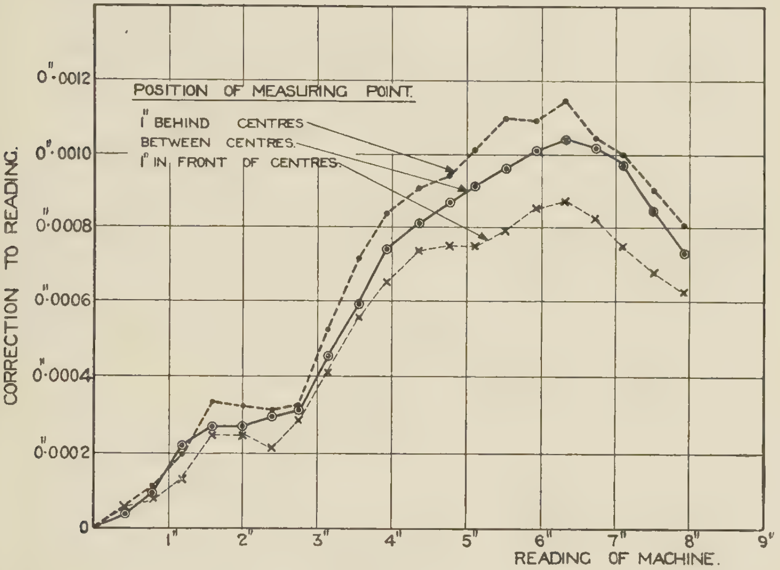


Fig. 289.

Against this it may be argued that, in calibrating an instrument by the usual procedure of measuring a series of standards of known sizes, the effect of any lack of straightness in the "ways" is taken account of automatically. This is quite true; but, on the other hand, it is not always realized that such a calibration becomes questionable after an interval of time during which the "ways" may have become worn, or distorted through secular changes in the metal. With the principle of alignment obeyed, such alterations would have a negligible influence upon the original calibration of the instrument.

Form of Measuring Machine Beds.

It seems to have become an established practice for the beds of end-measuring machines to be machined and scraped with the upper surface in the form of a vee and a flat. This method of construction is obviously expensive, and entails special methods of testing to verify the straightness.* On the other hand, a cylindrical form of bed, as suggested to the writer some years ago by A. J. C. Brookes, offers several advantages.

First of all, this form lends itself to what is, perhaps, the most accurate method of machining—cylindrical grinding. As regards straightness, this is ensured, provided parallelism is obtained in the grinding. This, of course, can be verified by simple micrometer measurements.

Satisfactory fitting between the bed and the headstock and tailstock can be obtained by the simple process of boring the latter parts to suit the diameter of the bed ; the usual method of scraping and "fitting" is rendered unnecessary. To prevent such parts turning on the bed, they can be located by tail-pieces bearing against another cylindrical rod arranged with its axis parallel to that of the bed and attached to it in some suitable manner.

Flexure of Measuring Machine Beds.

In designing the bed of a measuring machine, careful attention should be paid to its stiffness, with the view of minimizing its distortion when under the influence, not only of the dead-weight of other parts of the machine, but also of the variable loading caused by movements of slides and carriages along it. The effect of mounting heavy pieces of work in the machine for measurement has also to be borne in mind. It is clearly useless to spend time in finishing a bed to a high degree of accuracy as regards flatness if it becomes distorted when put into actual use.

It may be of interest in this connection to quote one or two typical defects in machines which have come under the writer's notice.

When making comparisons between two rather large gauges in an end-measuring machine, such as is shown diagrammatically in Fig. 290, it is usual to support them, in turn, on the bed of the machine between the contact faces. This, of course, is liable to bend the bed and so alter the distance between the head and tailstocks. For gauges of equal weight, the effect would be the same in both cases and the comparison of their sizes would not be affected. On the other hand, when measuring, say, the diameter of a large cylinder by comparison with the length of a bar gauge, a false result is probable owing to greater flexure of the bed when the heavier cylindrical gauge is placed upon it.

---

* See Chapter X.

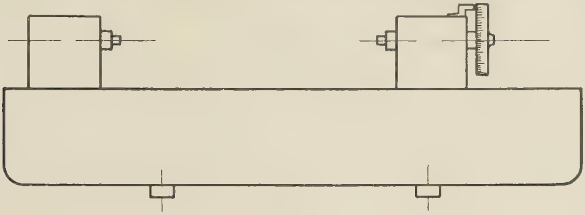


Fig. 290.

In such cases, it is difficult, even with a very massive bed, to be certain that no error is entering into the result, and the most satisfactory remedy is to support heavy gauges independently of the bed of the machine.

Turning now to another type of comparator as used for line standards,* one of the earlier designs, shown diagrammatically in Fig. 291, was provided with a slide A, bolted to the bed plate behind the tank B, so that the micrometer microscopes C could be set at any required distance apart up to about a metre. The tank con-

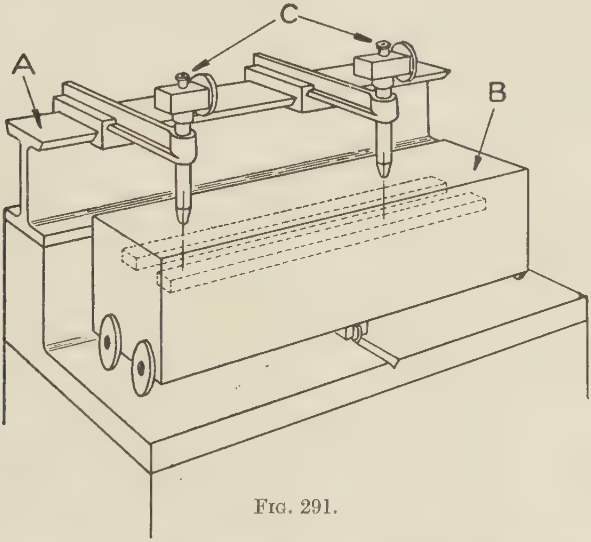


Fig. 291.

---

* See Vol. I. p. 25.

taining the two line standards immersed in water could be traversed across the bed plate on wheels, so as to enable the two line standards to be brought in turn under the microscopes. Two central wheels at the front and back, running in a vee groove, served to guide the tank as it was moved across the bed.

Now to obtain a true comparison between the two scales, it is essential that the distance between the microscopes should remain quite constant. It was found, however, with this particular design, that this distance changed appreciably when the heavy tank was moved from one working position to the other. The weight of the tank caused flexure of the bed plate, which was communicated to the microscope slide bolted to it. Had the flexure remained constant, the accuracy of the comparison would not have suffered, but, varying as it did with the position of the tank, it gave rise to an appreciable error.

Theoretically, the resulting error in the comparison should have averaged out in the usual process of repeating the observations with the scales interchanged, but it was found that this did not serve, as the error varied erratically from time to time. It was not until the microscope slide was released from the bed plate and allowed to rest freely upon it on three feet, that reliable comparisons could be obtained.

The Thrust of Micrometer Screws.

In general, there are two arrangements of micrometer screws, (*a*) in which the screw is restrained from moving axially, and (*b*) in which the nut is fixed. Let us consider these in turn from the point of view of the best means of taking the axial thrust.

In the first case, the necessary constraint can be applied either to the end of the screw, as at A in Fig. 292, or against a collar on it, as at B. Considering the end-thrust arrangement, A, it will be seen that, provided the abutment face is accurately square to the axis of the screw, *or* the abutment point at the end of the screw lies

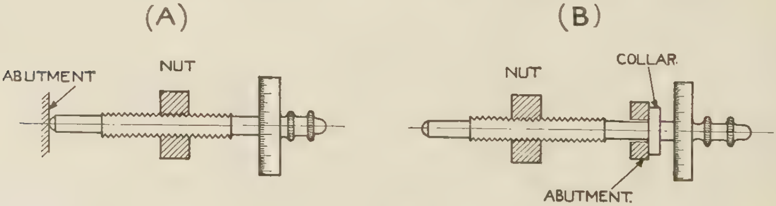


Fig. 292.

accurately on the axis, there will be no periodic to-and-fro motion of the screw as it is revolved, and the motion of the nut will be free from "periodic error". On the other hand, if the abutment face is inclined and, in addition, the point of the screw is not on its axis, the screw will suffer a to-and-fro motion in the direction of its axis during each revolution. This motion will be communicated to the nut in addition to the translation arising from the rotation of the micrometer screw.

From Fig. 293 it will be seen that the screw will oscillate from its mean position by an amount equal to $e \, . \tan \theta$ in both directions, e being the eccentricity of the point of contact at the end of the screw, and θ the error in squareness of the abutment face. The axial motion of the screw will actually follow the ordinates of a sine curve having an amplitude of $\pm e \tan \theta$.

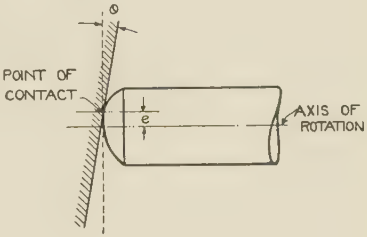


Fig. 293.

A similar state of affairs arises with a collar-thrust, as at B in Fig. 292. If the face of either the collar or the abutment is accurately square, there will be no axial motion of the screw; should they both be inclined, however, a periodic axial motion will arise, the magnitude of which will depend upon the diameter of the collar and the inclination of the face which is the more nearly correct. Thus, in Fig. 294, the maximum traverse of the screw from its mean position will be $\pm \frac{1}{2} d \, . \tan \theta$, and, as before, the motion will vary according to a sine law.

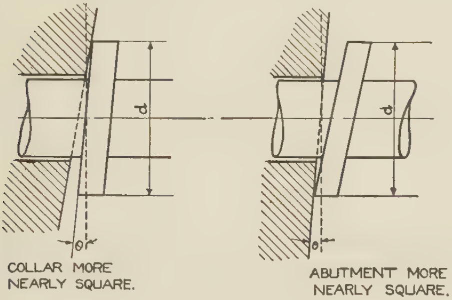


Fig. 294.

Turning to the case where the nut is fixed and the traverse of micrometer screw is communicated direct to a carriage or some other moving part of a measuring machine, the arrangements shown in Fig. 292 are still applicable, on the understanding that the abutment now forms part of the carriage and the nut is fixed to the bed of the machine. The same conditions as regards periodic error, therefore, apply as before.

Every endeavour should be made in the design and construction of measuring instruments to avoid periodic errors in the micrometer motions, since, unlike progressive errors, they cannot readily be compensated for by simple correcting devices. Where a collar-thrust has to be used, good workmanship and accurate machining should ensure satisfactory squareness of the faces. The simple type of end-thrust shown at A in Fig. 292 should be avoided as far as possible. In addition to the risk of periodic error, it is usually difficult to keep the contact clean. The pressure is concentrated practically at a point, and, owing to the relative motion between the abutment and the rotating point, there is a strong tendency for corrosion to occur round the contact in the absence of satisfactory lubrication.* This tendency, it may be mentioned, still exists, even if an agate abutment be used.

The alternative arrangement shown in Fig. 295 overcomes both difficulties as regards periodic error and fouling of the contact. The pressure is transmitted from the micrometer screw to the abutment through a ball-ended strut which fits loosely in countersunk holes drilled in the two members. Such a strut is made most conveniently by soldering steel balls to the ends of a short length of rod. The exact alignment of the holes in the abutment and in the micrometer spindle is not essential so long as the strut is made fairly long and the two holes are reasonably in line. Satisfactory lubrication can be obtained by packing the holes with grease.

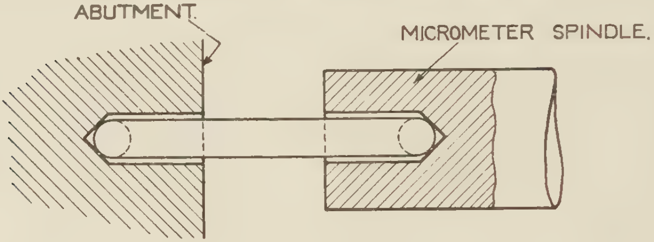


Fig. 295.

Another method of taking end thrust, which can be applied when it is desired to restrain the screw axially and, at the same time, support it off the fixed abutment, is shown in Fig. 296. The abutment has a cylindrical projection, which is a good running fit in a conical-ended hole bored in the end of the screw. The thrust is taken between the cone and a hardened steel hemisphere, the lapped base of which bears against the end of the supporting cylinder.

---

* See "The Rusting of Steel Surfaces in Contact," G. A. Tomlinson, *Proc. Roy. Soc.* A, vol. 115, p. 472 (1927).

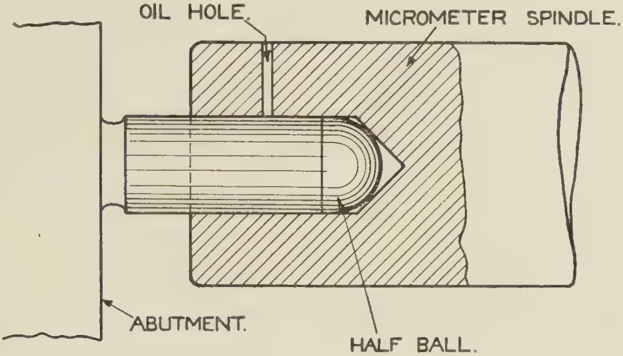


Fig. 296.

The Use of Flexible Steel Strips.

The last fifteen years or so have seen increasing application of flexible steel strips to the mechanisms of measuring machines and instruments.

So far as gauge-measuring instruments are concerned, the practice was first introduced by E. M. Eden at the National Physical Laboratory about 1916. The strips perform the function of hinges and pivots with entire elimination of backlash. A few typical examples of their uses are given below.

The arrangement shown in Fig. 297 illustrates a mechanism in which a block A is attached by a pair of flexible strips to a base B, in such a manner that it is capable of a limited endwise motion. The block remains parallel to itself and, for small displacements from its normal position, its distance from the base does not alter appreciably.

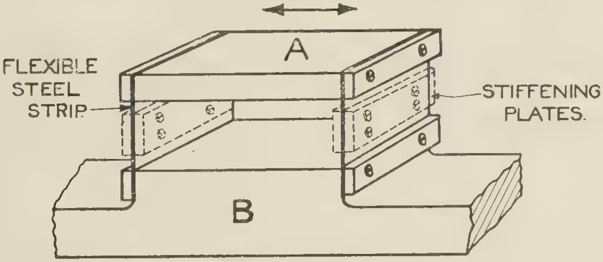


Fig. 297.

It will be understood that the resistance to bending offered by the strips increases with their flexure, but the force required for any given displacement can be decided at will, within a wide range, by choosing suitable dimensions for the strips.

An important feature of the arrangement is that, provided the strips are not too narrow in comparison with their height, they offer considerable resistance to any twisting effect. Any tendency for the strips to buckle under the weight of the block can be prevented by reinforcing them with side plates, as shown dotted in the figure.

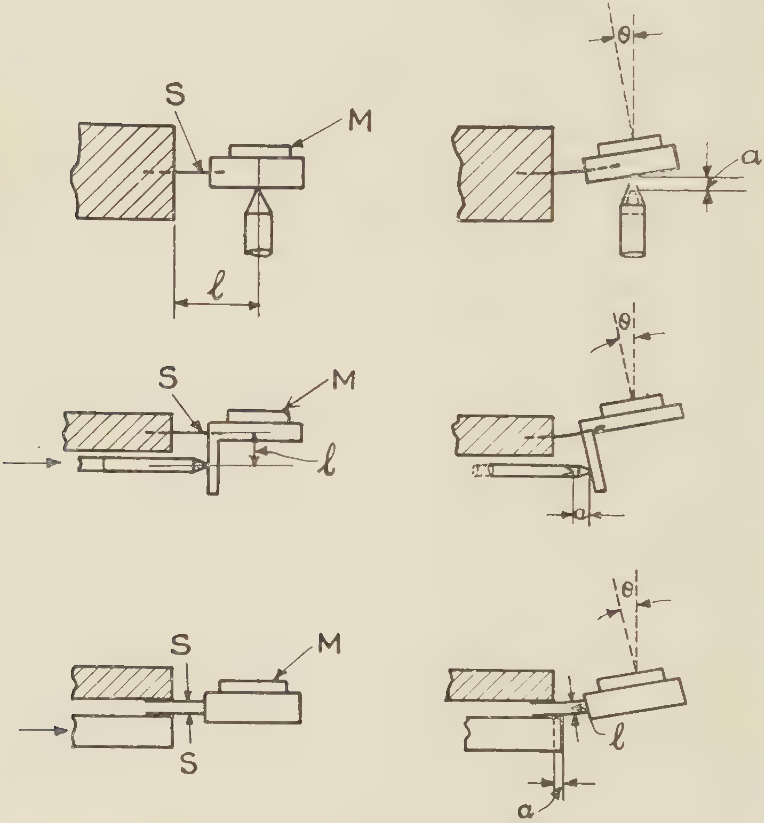


Fig. 298.

Many types of measuring instruments have an optical form of indicator, the essential part of which consists of a deflecting mirror. Instead of mounting such a mirror on the usual pivots, it can, with advantage, be supported on a thin steel strip, as shown diagrammatically in Fig. 298. Three arrangements are shown whereby the linear displacement a of a moving member can be made to deflect the mirror M, the latter being cemented to a small plate which is attached by a strip S to a fixed part of the machine (shown shaded).

The last arrangement is of particular interest and is known as the " twin strip " mechanism. The plate upon which the mirror is fixed is coupled by means of two parallel steel strips to the moving, as well as to the fixed part of the instrument. It can readily be seen that if the strips are separated by a distance l, a small displacement a of the moving member will produce a deflection, θ, of the mirror approximately equal to a/l. The deflection of the ray of light will, of course, be double this angle.

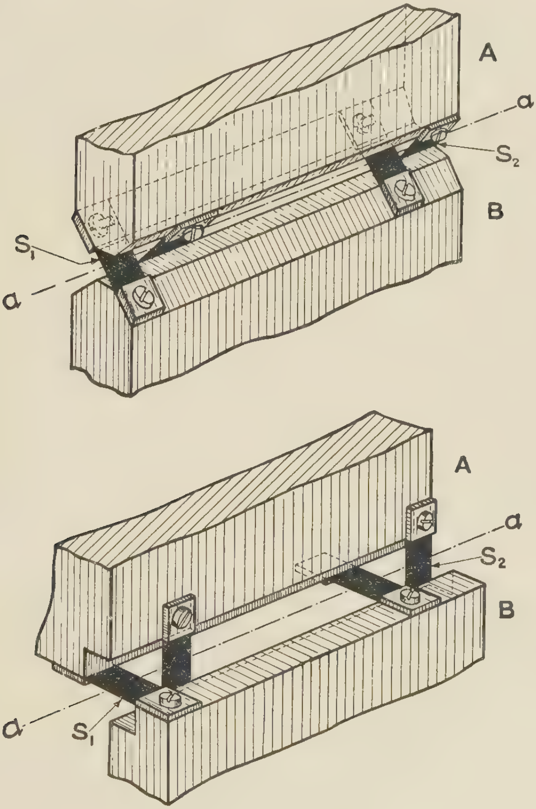


FIG. 299.

An obvious limitation to the replacement of pivots by the steel-strip form of hinge occurs when it is required that the deflection of the mirror shall be strictly proportional to the linear displacement. This condition cannot be achieved with a strip connection, as the position of the axis of rotation of the mirror varies with the amount of bending of the strip. A very close approximation to a constant axis of rotation can be arrived at, however, by the use of the "crossed-strip" coupling, diagrams of which are shown in Fig. 299. The movable member A, which may carry a mirror, or which often constitutes a lever in some magnifying mechanism, is connected to a fixed member B by two pairs of strip, S_1 and S_2. The strips of each pair lie in a plane, and the two planes are arranged at right angles. Small relative angular movements between the two members then take place about an axis *aa* forming the line of intersection of the two planes. Two arrangements of the strips as commonly used are shown in the diagram, but the principle is the same in each.

Micrometer Screws.

The frequent occurrence of micrometer screws in measuring instruments calls for some attention under the heading of this chapter.

In deciding upon the general proportions of a micrometer screw and its nut, and the material of which they are to be made, due regard should be paid not only to the initial accuracy to which they can be produced, but also to their ability to maintain their accuracy in use.

Tool steel in a normalized, unhardened condition is almost invariably used for micrometer screws on account of its wearing qualities. On the other hand, special care has to be taken in cutting the thread in this material to obtain a clean, smooth surface. No satisfaction is to be expected from a screw with surface defects, even if an attempt has been made to remedy the trouble by prolonged "running-in" with the nut. This finishing process can, however, be used with advantage to smooth out the minute irregularities which are present in even well-cut screws, more uniform contact between the screw and nut being thereby ensured. The use of even the finest abrasive to assist in this process is not to be recommended, owing to the impossibility of finally freeing the screw threads from the embedded particles, the presence of which would cause continual wearing of the threads when in service.

As regards the form of the thread, the vee-shape appears most satisfactory, provided the crests and roots are cleared so as to confine the contact to the flanks of the threads. A liberal area of bearing can be obtained by using rather a fine thread angle, such as is shown in Fig. 300. The roots of the threads of both screw and nut should be taken almost to a sharp point, but the crests should be left flat. The importance of equality of thread angle in the two components so as to ensure satisfactory flank contact should be appreciated.

The presence of backlash between a micrometer screw and its nut is usually considered very undesirable. More often than not, however, the screw works against a definite thrust in one direction, and, provided the setting is always made so as to oppose the thrust, the presence of a limited amount of backlash has no detrimental effect upon the accuracy.

As regards the accuracy of pitch of micrometer screws, it is the usual practice to cut the threads on special lathes or machines fitted with lead screws of accurate pitch. Since, in the majority of larger measuring instruments, suitably formed "corrector bars" are fitted to compensate for residual pitch errors in the micrometer screw, it is unnecessary in such cases to strive for more than reasonable accuracy in the screwing. Provided the errors are of a general progressive nature, they can be readily compensated for by the device mentioned, but local irregularities in the screwing should be avoided as far as possible. Not only are these errors difficult to compensate for, but they also constitute high places on the thread which are particularly susceptible to wear, and cause deterioration in the accuracy of the micrometer screw.

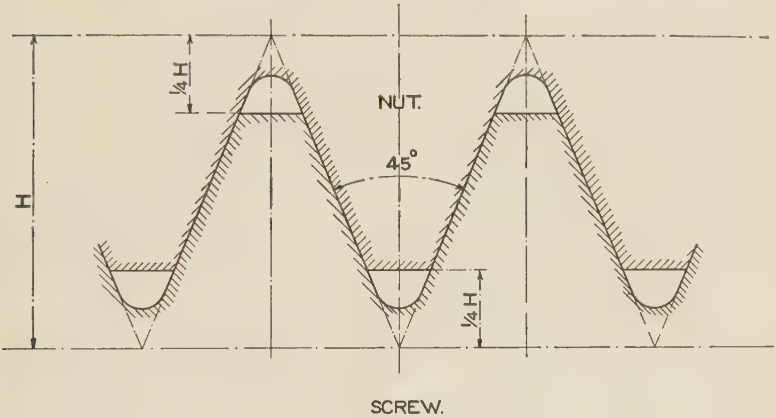


Fig. 300.

The accuracy of the pitch of a micrometer nut is of secondary importance provided it does not differ seriously from the pitch of the screw and so localize the contact at the end threads. Given reasonably equal pitches, a satisfactory bearing between the screw and the nut should readily be obtainable by the process of running-in referred to above.

When designing a measuring machine, it is important to arrange that the micrometer screw shall be adequately protected from dust and accidental knocks. Definite provision should also be made for periodical cleaning and lubrication.

Before leaving the subject of micrometer screws, it may be of interest to draw attention to an arrangement designed by J. E. Sears, by means of which it is possible to obtain readings of a micrometer in either inch or millimetre units. The contrivance is based upon the relationship between the two units expressed by the formula 1 inch = 25·4 millimetres, which is correct to within one part in a million. A description of the arrangement will be found in Vol. I. page 280 of this work.

Fine Adjustments.

Fine adjustments are provided on measuring and other instruments for accurately locating one component with respect to another, or to the general body of the instrument. Many different devices are used according to the particular requirement, and it may be of interest to mention a few which possess rather special features.

Finely-threaded screws are very frequently used for adjustment purposes, but in some cases the setting required is of so delicate a nature as would necessitate the use of a screw with an unusually fine pitch. Advantage can then be taken of a differential screw adjustment, in which almost any degree of sensitivity can be obtained even with screws of relatively coarse pitches and corresponding robustness.

An example of such an arrangement, which can also be applied to micrometer motions, is shown in Fig. 301. The central spindle is screwed with two independent threads, S_1 and S_2: the former engages with a fixed nut, whilst the latter screws into a sliding nut A, which is prevented from rotating by a projecting pin B, working in a slot. The two screws have slightly different pitches of the same hand. For example, S_1 might have 20, and S_2 25 threads per inch. One revolution of the spindle would then cause the member A to be displaced a distance equal to $\frac{1}{20}-\frac{1}{25}$ inch, *i.e.* 0·01 inch. The arrangement is therefore equivalent to a single screw thread having 100 threads per inch.

The sensitivity of the adjustment obtained from a single screw can be increased, where circumstances allow, by mounting it on a flexible arm, as at A in Fig. 302. By choosing suitable dimensions for the arm, the actual movement of the part to be adjusted can be made relatively small for an appreciable rotation of the screw, the bulk of the axial displacement of the screw in its nut being taken up by deflection of the arm.

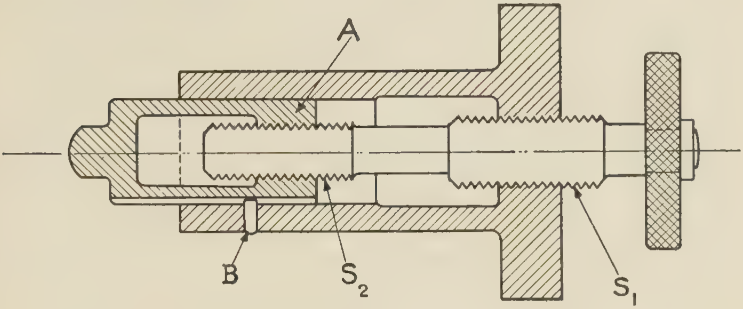


Fig. 301.

A similar arrangement is shown at B in the same figure. Here the lever takes the form of a steel strip, the outer end of which is forced into contact with the part to be moved by an adjusting screw situated some distance back from the end of the lever.

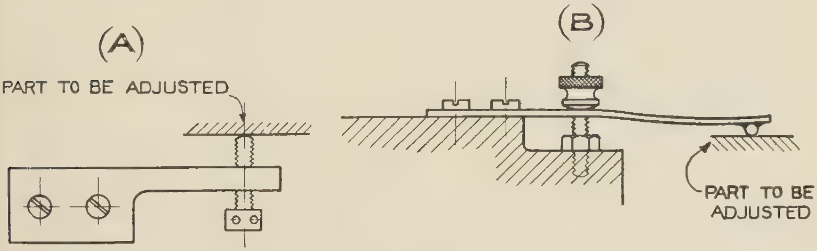


Fig. 302.

Before leaving adjusting screws, brief mention may be made of methods used for locking the screws so as to preserve a given setting. Locknuts are unsatisfactory for this purpose, as it is very difficult to bring them into operation without disturbing the adjustment. The use of a split hole and pinching screw, as in Fig. 303 (A), overcomes this trouble.

Another satisfactory method is shown at B in the same figure. Here the holes for the adjusting screw and locking pin partially intersect. By placing the locking pin S in position when tapping the hole for the adjusting screw, the thread is continued in the side of the shank of the pin. The adjusting screw can then be securely bound in position without disturbing its setting by tightening the nut on the end of the pin S.

Some interesting examples of the application of adjusting screws will be found among the descriptions of snap gauges on page 9 *et seq.*

The principle of a simple but ingenious form of adjustment, as used on the machine designed by E. M. Eden for measuring the diameters of screws, will be gathered from Fig. 304. A plate A, with three ball-ended feet, can be considered as located by the usual hole, slot and plane method (see Fig. 283A). The foot *a*, which rests in the vee slot, has an eccentric shank, so that by rotating it in the plate the angular position of the latter can be altered over a limited range, with respect to the base upon which it rests. The fineness of the adjustment can be varied at will by giving suitable eccentricity to the pin, which, after the adjustment, can be locked by some such arrangement as that shown.

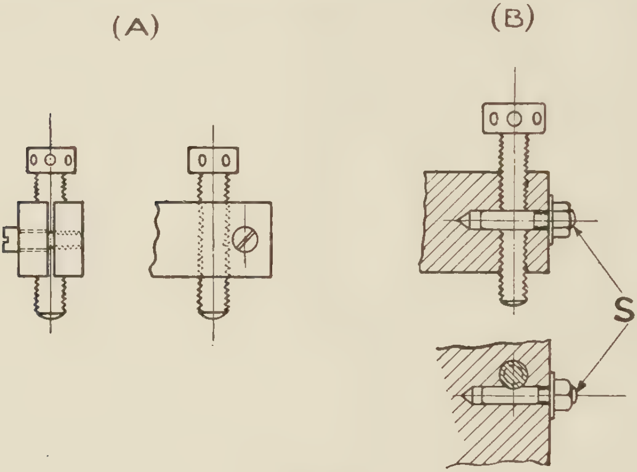


Fig. 303.

Turning now to measuring machines fitted with a micrometer screw, the accuracy of setting is usually improved if the machine has a fine adjustment on the micrometer drum. It is desirable that this adjustment should be as simple as possible, especially as regards the means of bringing it into or out of action. In the

Newall type of machine * the adjustment consists of a tangent screw at the end of an arm which can be locked at will on to the micrometer spindle. The troublesome feature of this arrangement is that the tangent screw, which of course is always operated in one direction, sooner or later reaches the end of its travel and has to be unscrewed before it can be brought into use again. The action can be made continuous by using a worm and worm-wheel, and in the travelling microscope designed at the National Physical Laboratory,† the plate carrying the bearings for the worm is pivoted at one end so that the worm can readily be engaged or taken out of mesh, as required.

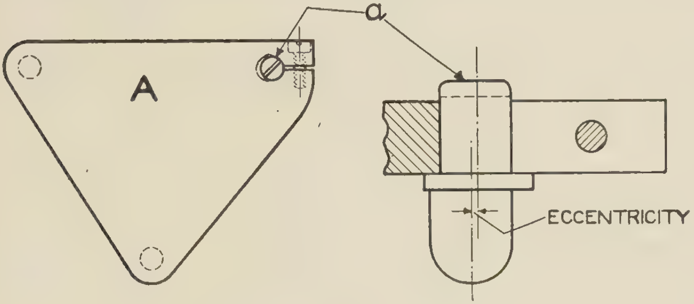


Fig. 304.

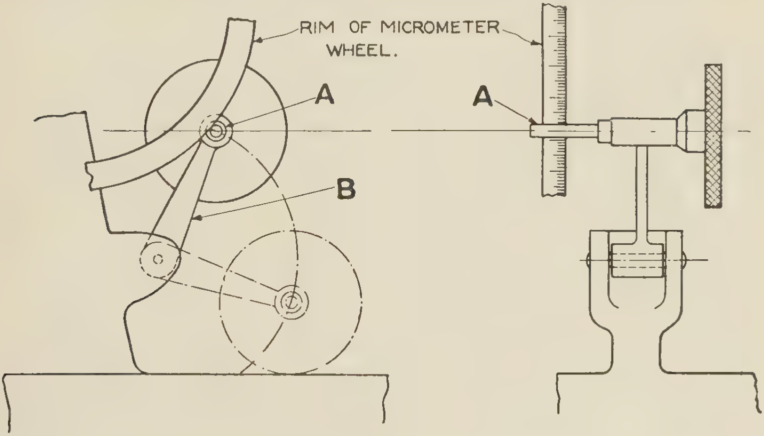


Fig. 305.

In cases where the motion of the micrometer is sufficiently free,

---

* See Vol. I. p. 267.

† See p. 221.

it is difficult to conceive a simpler arrangement than that used by Bingham Powell on his machine for measuring the pitch of screws.* Here, slow rotation of the micrometer wheel is effected by a small, rubber-covered, friction drum, A (Fig. 305), which is attached to a pivoted arm, B. When not in use, this arm drops by gravity and leaves the micrometer wheel free.

---

* See *Amer. Mach.* vol. 47, p. 1065 (1917).

ADDITIONAL REFERENCES FOR CHAPTER XIV

"The Mechanical Design of Instruments," W. Rosenhain, *Proc. of Opt. Convention*, p. 31 (1905).

"Scientific Instruments, their Design and Use in Aeronautics," Horace Darwin, *Aeronautical Journal* (July 1913).

"Variance of Measuring Instruments," F. J. Schlink, *Bureau of Standards Bull.*, vol. 14, p. 741 (1918); also *Engineering*, vol. 107, p. 220 (1919).

"Expression of the Accuracy of Measuring Instruments," A. Barbagelata, *L'Elettrotecnica* (June 25, 1919).

"Wear of Micrometer Screws" (account of series of tests made by Messrs. Zeiss), *Machinery*, vol. 27, p. 521 (1926).

"Device to Prevent Backlash in Scientific Instruments," J. R. Milne, *Phil. Mag.*, vol. 18, p. 336 (1909).

"The Geometric Design of Scientific Instruments," J. A. Tomkins, *Instrument World*, vol. 1, p. 229 (1928).

"Principles of Instrument and Apparatus Design," W. Kniehahn, *V.D.I. Zeit.* (Berlin), vol. 72, p. 1773 (1928).

"Angular Movement for Gauging Devices," *Machinery*, vol. 34, p. 142 (1929).

CHAPTER XV

MEASUREMENT OF GEARS

The demand for quieter running automobile gears and for increased efficiency and durability in heavy duty reduction gearing, such as is used in conjunction with marine turbines, has been largely responsible for the steady improvement which, in latter years, has taken place in methods of gear production. The advance in the quality of the product created, in turn, the usual need for more accurate methods of testing, with the result that many different designs of gear-measuring apparatus have appeared from time to time. Descriptions of some of the more notable machines and instruments are appended.

Zeiss Optical Gear-Tooth Calliper.

This instrument is intended for measuring the thickness of gear teeth at definite distances from the top. The measurements are made between the tips of a pair of parallel jaws A, Fig. 306, the distance between which can be adjusted by a finely threaded screw B. The distance h from the top to where the thickness t is measured is controlled by an edge C, the position of which can be adjusted by the screw D. The measurements t and h are read on glass scales housed in the body of the instrument and viewed through a small eyepiece E, with the instrument held against the light. The appearance in the eyepiece is indicated in Fig. 307, which is about half-size. The scales are divided to read direct to 0·001 inch. Thus, in the example given, $t = 0{\cdot}2345$ and $h = 0{\cdot}352$ inch.

The obvious criticism of such an instrument is the probability of wear taking place at the tips of the measuring jaws, which would affect the zero positions of both scales. Whilst the absolute values of t and h would thereby be rendered somewhat doubtful, wear would not affect the use of the instrument as a comparator for checking the uniformity of the teeth round a gear, or for obtaining their

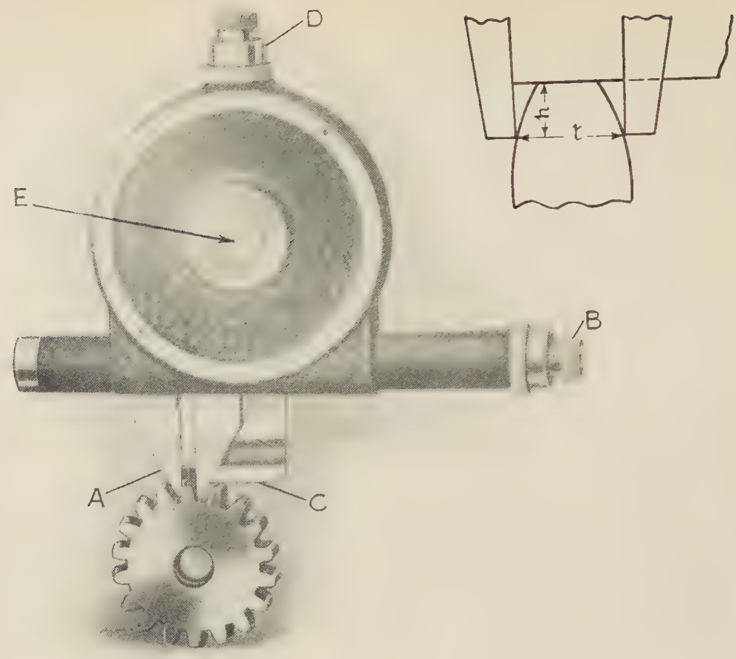


Fig. 306.

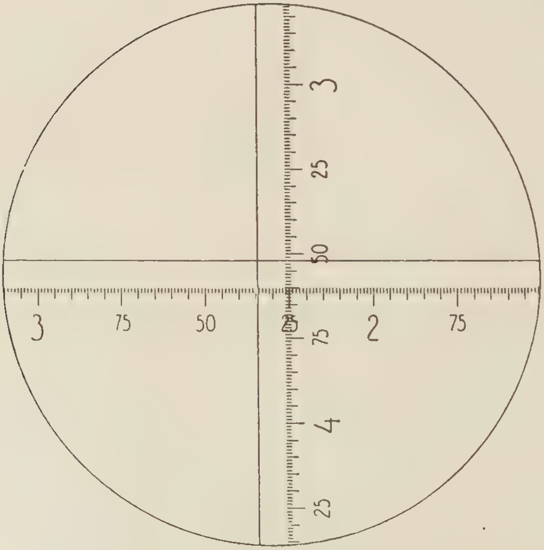


Fig. 307.

actual thicknesses, provided a standard gear of known dimensions is available.

It should be noted that the instrument gives no information as to the relative spacing of the teeth, and that its measurements of tooth thickness depend upon the outside diameter of the gear being concentric with the pitch circle of the teeth—a condition which is, of course, not essential so far as satisfactory running is concerned.

Pratt and Whitney " Odontometer ".

This instrument, as will be gathered from Fig. 308, is in the form of a hand-measuring tool, and serves not only for checking the equality of pitch between corresponding flanks, but also for indicating the accuracy of the profile of involute teeth.

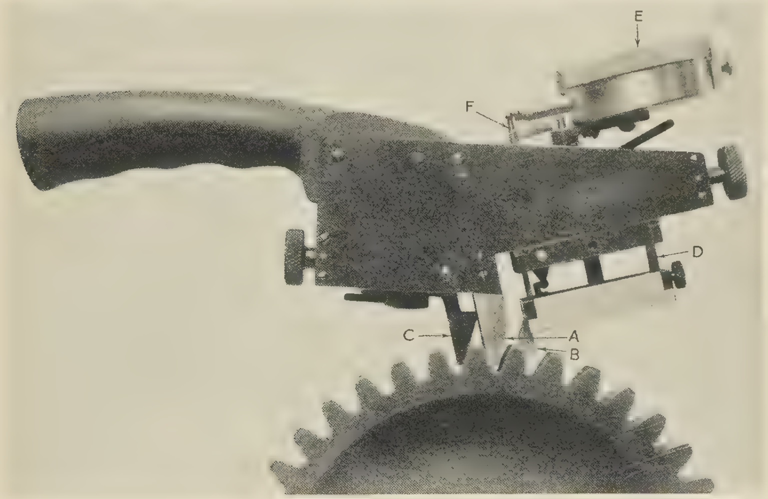


FIG. 308.

Contact is made on corresponding flanks of neighbouring teeth by the parallel faces of two tongues A and B, the former being fixed, whilst the latter is attached to an indicating mechanism and is capable of small movements normal to the flank of the tooth. A third contact C serves to hold the tongue A against the flank, and, together with B, is adjustable so as to suit different sizes of teeth.

In operation the instrument is placed upon a gear, as shown, and is rocked so that the contact faces of A and B slide down the flanks of the teeth, and any variations shown by the indicator are noted. This process is repeated all round the gear.

If one considers two involutes drawn to a given base circle, as in Fig. 309, it is clear from the properties of the curves that, no matter at what position it is measured, the normal distance *l* between them is constant, and is equal to the length of arc intercepted on the base circle. It is this normal distance *l* which is gauged by the instrument under consideration, the measurements being necessarily confined between two positions A and B, indicated in the diagram of the gear.

The indicating mechanism is of a simple character. The movable tongue B, Fig. 308, is fixed to a block which is hinged to the body of the indicator by a pair of parallel steel strips D. Its movements are communicated to a dial indicator E by a 5 to 1 lever F; each division on the indicator dial represents a movement of the tongue of 0·0002 inch.

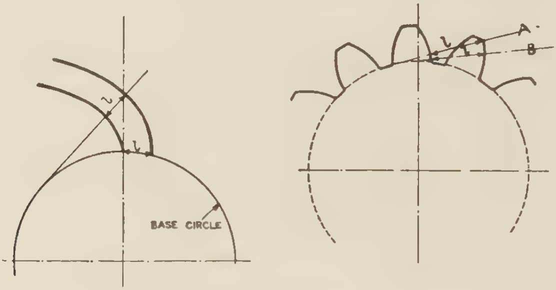


FIG. 309.

Variations of the indicator as the instrument is rocked on a given pair of teeth denote errors in the involute profile; whilst alterations in the mean reading, when applied to successive pairs of flanks, indicate lack of uniformity of pitch.

This instrument can be applied to helical as well as spur gears. It has the advantage over many similar devices in that the measurements of pitch are made between corresponding flanks of the teeth instead of between their centre lines, or the centres of the spaces between them.

Maag Tooth-Measuring Instrument.

A somewhat similar type of instrument to the above is one made by Messrs. Maag of Zurich. It is shown applied to a spur gear in Fig. 310. The operating contacts are *a* and *b*, the former being a flat surface, whilst the latter is attached to the indicator mechanism. A third contact *c*, the distance of which from the surface *a* can be adjusted by means of the screw *g*, serves to hold the surface in contact with the flank of the tooth. For teeth of different pitches the block to which the contacts *a* and *c* are fixed can be moved relative to *b* by an adjusting screw *f*.

The instrument is operated in exactly the same manner as the "odontometer"; variations in the reading of its indicator (one division of which represents 0·01 mm.) denote either departures of the flanks from true involute form, or irregularities in pitch from tooth to tooth, according to whether the instrument is rocked round a tooth in one position, or is applied to different teeth in succession.

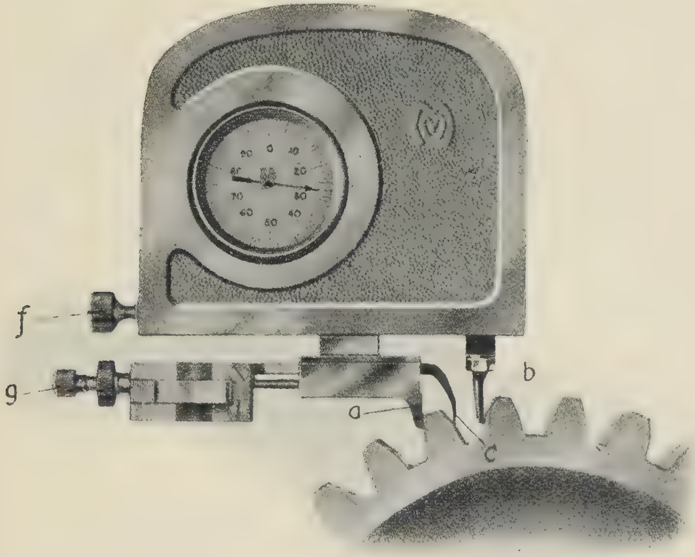


Fig. 310.

In addition to its use as a comparator, this instrument will serve to measure the actual circumferential pitch between corresponding flanks of neighbouring teeth. For this purpose a comparative reading of the instrument has to be taken upon a reference piece of the form shown in Fig. 311. The distance between the two parallel gauging surfaces of the reference piece must, of course, be known, but that is a matter of simple measurement. Having obtained absolute measurements of the pitch round a gear, it is possible to find, to a limited accuracy, the actual diameter of its base circle from the average pitch and the number of teeth.

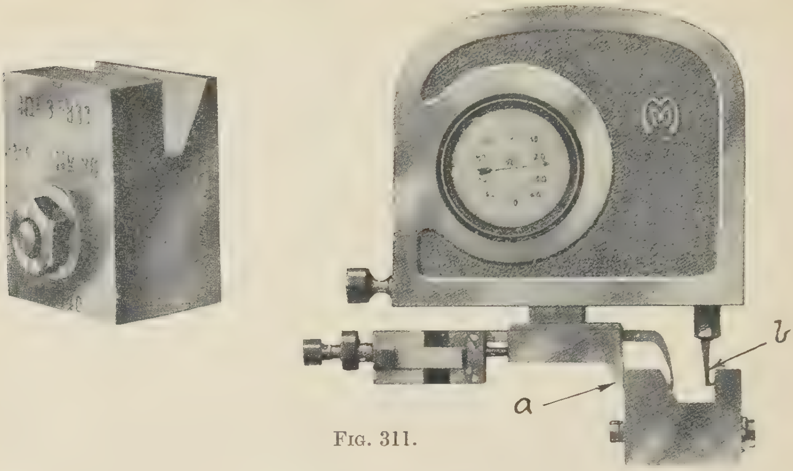


Fig. 311.

Maag Gear-Tooth Profile Testing Appliance.

The general principle of this machine is shown in Fig. 312. The gear to be tested has coupled to it a concentric disc A, having a diameter equal to that of its nominal base circle. The gear and disc are rotated by a translatory movement of a slide B, which is pressed

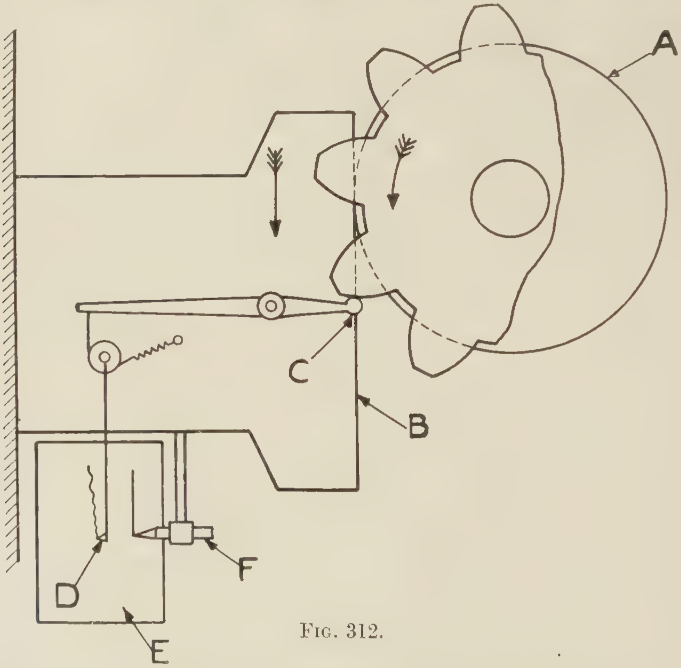


Fig. 312.

into contact with the periphery of the disc. This slide carries an indicating mechanism, of which the ball-ended point C is kept in contact with one of the tooth flanks. Since it is arranged for the path of the ball-ended point to be tangential to the base circle disc, it is clear that, in the case of a true involute profile, the indicator lever will suffer no deflection as the gear rotates and the point passes along the flank. On the other hand, the presence of errors in the profile would affect the indicator, and its recording pen D would trace a wavy, or inclined line on the chart E, instead of one which is straight and parallel to the base line marked by the pencil F, rigidly attached to the slide B.

The indicator gives a magnification of 250 times, and is arranged so that the profiles of both flanks of a tooth can be examined in turn and recorded on the same chart.

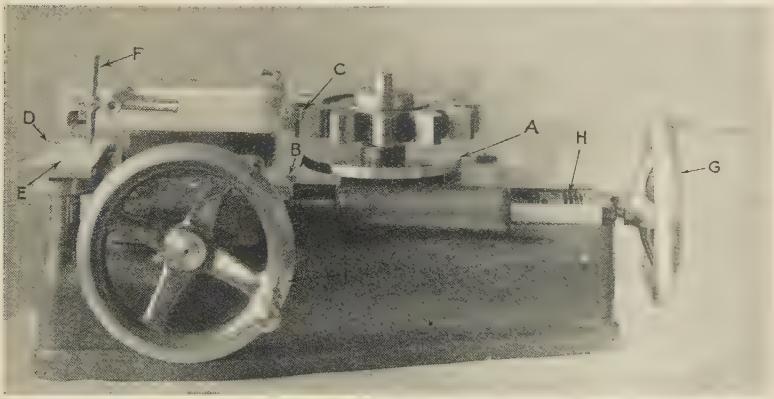


Fig. 313.

The actual machine is shown in Fig. 313, the lettering of which follows the diagrammatic layout of the previous figure. The base circle disc A, and the slide B, are brought into contact by turning the hand-wheel G, the spring H supplying the necessary pressure at the contact. To obtain a trace for a tooth, the slide B is advanced slowly by turning a second hand-wheel I. At the same time, the disc with the gear wheel attached is driven round by frictional contact with the slide and the point C of the indicator travels along one side of the tooth.

Zeiss Involute Testing Machine.

Given the diameter of the base circle of a gear, the Zeiss instrument about to be described enables an accurate test to be made upon the involute profile of the teeth. Should the base circle be unknown, it enables the diameter to be determined which is best suited to the involute form of the teeth.

The action of the instrument is based upon a fundamental geometrical property of the involute curve and is illustrated in Fig. 314, where PQ is an involute to a base circle PB, the tangent at P being PT. If the base circle be imagined to revolve about its centre O, carrying the involute with it, and at the same time moving the tangent line to the right without any circumferential slipping, the point P on the tangent will always remain on the involute as the latter moves, and will occupy in succession such positions as P_1, P_2, P_3, etc. On the other hand, should the curve PQ not be a true involute, the point P will not follow it during the motion, and the errors of the curve from true involute form can be measured by noting the departures of the point for different positions during the rotation. This is what the instrument accomplishes.

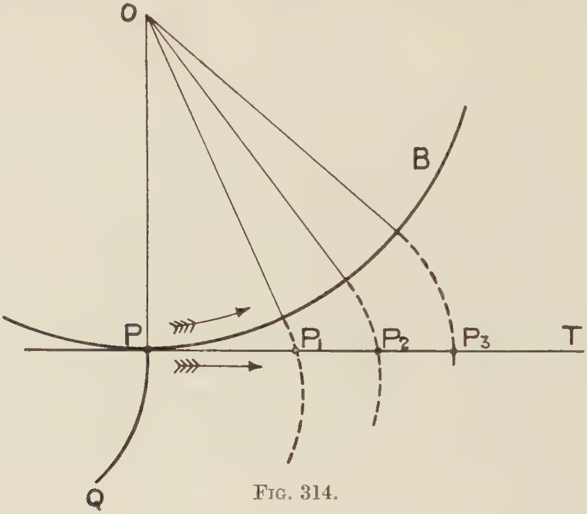


Fig. 314.

The gear to be tested is mounted on an arbor between vertical centres and is attached to a sector of a master base circle A, Fig. 315, having a radius of 150 mm. Contact with the flank of a tooth is made with a ball-ended stylus B, mounted on a carriage C, which can move on rollers along a cylindrical rod D. Rotation is given to the gear and the master base circle by movement of a steel tape E. A corresponding angular motion is also transmitted to a steel guide-plate F, which can turn about an axis G. A roller H, attached to the carriage C, bears against the side of this plate, so that, as the latter revolves about G, the carriage is moved sideways through distances equal to the product of the angle of rotation of the gear and the radial distance of the stylus B. Any departures of the tooth profile from a true involute will cause the stylus to move to the left or right relative to the carriage. These movements are magnified 500 times on the scale of a suitable indicating device, which is shown diagrammatically in the figure. When testing the right-hand flank, the gear is rotated anti clockwise and the carriage moves from left to right; for the opposite flank, the motions are reversed. Pressure can be applied to the indicator stylus from either one side or the other in order to keep it in contact with the flank of the tooth under observation.

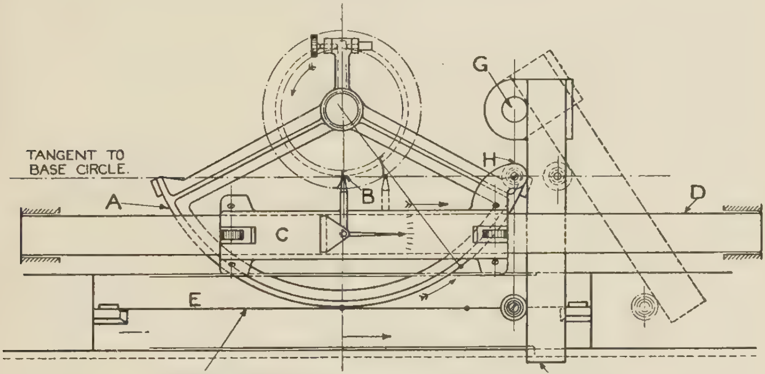


Fig. 315.

Before testing a gear it is important that the stylus should be set so that its distance from the centre is equal to the radius of the nominal base circle, and for this purpose the supports of the guide rod D can be moved bodily to or from the axis of rotation.

The instrument, with a gear mounted ready for test, is illustrated in Fig. 316. The screw adjustment for the radial position of the stylus is shown at A, the actual setting being made against an accurate scale viewed with a microscope B.

In addition to a direct reading indicator, the instrument is fitted with an autographic device which produces a record in the form of a continuous curve on a chart C. For a true involute profile, this curve becomes a straight line running from left to right.

Rotation of the gear and master base circle is given by the hand-wheel D; whilst a second wheel E enables the gear to be raised or lowered for purposes of adjustment and for examining the profile at different distances from the sides of the gear.

In order to test the behaviour of the instrument at any time, a ground steel disc 150 mm. in diameter is mounted between the centres, and the radial position of the stylus set accordingly by means of the scale and microscope. The stylus is made to engage, as in Fig. 317, with a clip attached to a steel band fastened at one end to the circumference of the disc, and held taut in the direction of motion of the indicator carriage. If the instrument is in correct adjustment, the pointer of the indicator should not deviate from its initial reading as the test disc and the master base circle are rotated together.

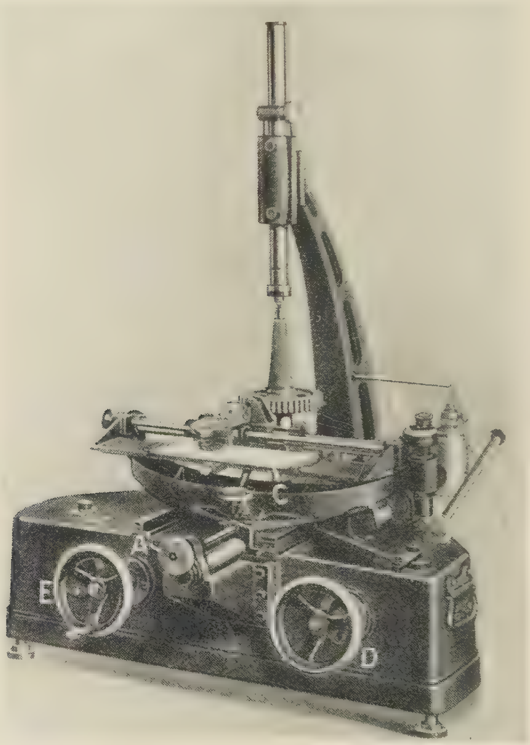


Fig. 316.

When it is required to ascertain the base circle of a gear, a succession of tests is carried out with the stylus set to different radial positions in turn. The position corresponding with the minimum deflection of the indicator as the stylus travels along the flank determines the base circle, the diameter of which is ascertained from the scale reading.

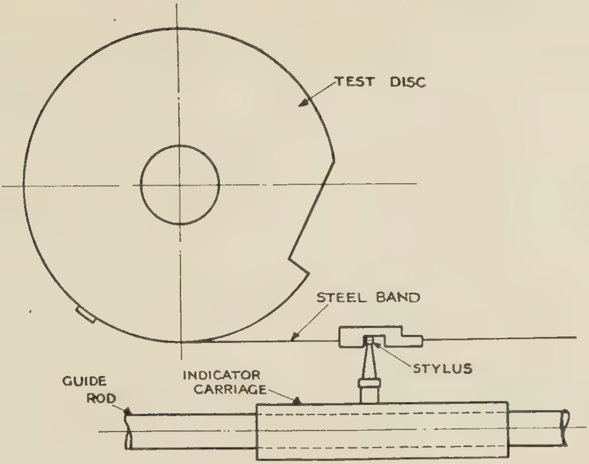


FIG. 317.

Saurer Gear-Testing Apparatus.

One of the forms of gear-testing machines designed by Messrs. Saurer of Switzerland is shown in Fig. 318. The apparatus is shown set up for testing the regularity of motion transmitted by a pair of helical gears. The latter are mounted on vertical spindles, the distance between which can be adjusted over a range of about 3 to

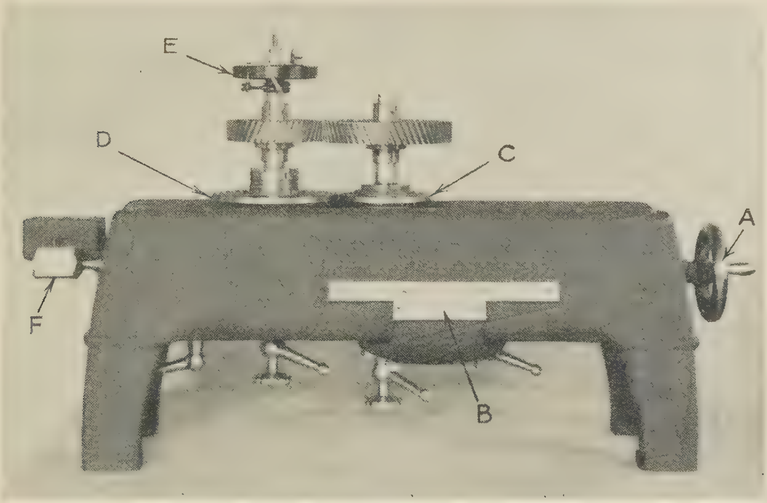


FIG. 318.

10 inches by a screw and hand-wheel A, against a scale B. Each spindle also carries a base-circle disc, the one on the right, C, being rigidly connected to the gear above it, whilst the other, D, is free to revolve on the spindle independently of the left-hand gear.

The distance between the spindles having been adjusted so as to bring the two discs into contact, the right-hand gear is rotated slowly by hand. This drives the second gear directly and, at the same time, the disc D is revolved by frictional contact with the disc C.

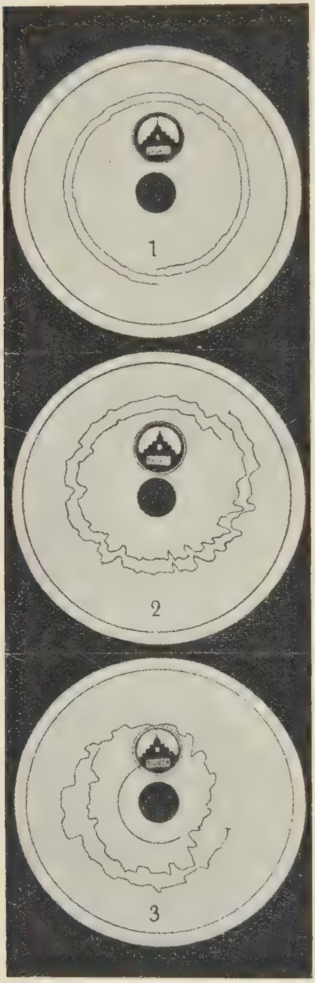


Fig. 319.

With correctly shaped and properly spaced teeth on the two wheels, their relative angular motion will be the same as that between their two base-circle discs; in other words, the left-hand gear and its disc D will revolve together. On the other hand, should the teeth be in error, a certain amount of relative angular motion will occur between the disc D and the gear above it. Provision is made for magnifying and recording such motion on a chart by an amplifying mechanism E, mounted at the top of the left-hand spindle.

Examples of traces obtained from three different pairs of gears are shown in Fig. 319. The practically uniform spiral line on the first chart indicates a satisfactory pair of gears, whilst the other two exhibit marked irregularities in the motion transmitted from one gear to the other.

Variations in the thickness of the teeth and spaces on the gears can also be tested by removing the discs and leaving the left-hand spindle free to move towards or away from the other spindle. The two gears are pressed closely into mesh, and, on rotating them, should the distance between the spindles not remain constant, the variation is shown by an indicator F, Fig. 318.

Bevel gears can be treated in a similar manner on another machine designed by the same firm. The gears are mounted on horizontal spindles, the angle between which can be adjusted within the range 52° to 150°. A properly proportioned friction disc A, Fig. 320, is mounted at the rear end of each spindle and these discs are coupled together by frictional contact with a tangent rod B. As in the case of the machine just described, only one disc is directly coupled to its gear spindle, the other being driven in the proper gear ratio from the first by means of the tangent rod.

Irregularities in angular motion between the gears are recorded autographically as before by a mechanism C, whilst endwise motions of the left-hand gear spindle are shown by a dial gauge D.

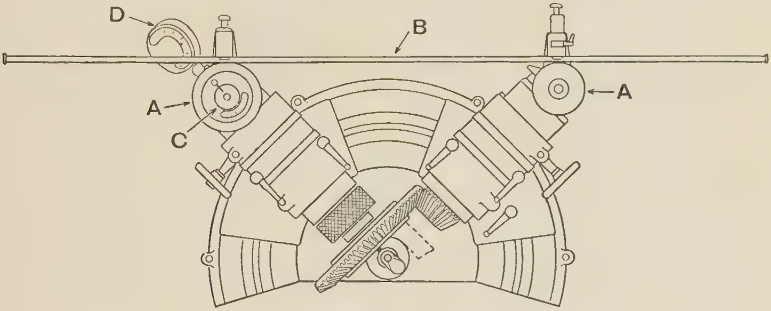


FIG. 320.

In tests of this kind, where two gears are involved, it is obviously desirable that one of the gears should comprise a master which has been proved, by some other means, to be free from errors. Without such a master gear it is practically impossible to apportion the errors shown by the machine between the two gears under test.

Zeiss Optical Gear-Testing Machine.

This machine, although now obsolete, is of interest, as the measurements are made upon optical images of the gear teeth instead of by the more usual method of mechanical contact.

The principle is shown in Fig. 321. The gear teeth, illuminated from behind by light reflected by a mirror, are viewed with a microscope through a special lens, split into two portions, as shown in the lower view of the figure. If the two halves of this auxiliary lens be brought together so as to form a unit, the appearance of a tooth in the microscope would be as at A. In actual use they are separated by measured amounts by means of micrometer screws, so that overlapping images of a tooth are seen, as at B in the same figure. Since, in the latter case, the image formed by each half of the lens is illuminated by light passed by the other half, the images present a greyish appearance except where they overlap; over this region the appearance is much darker.

It is clear that, should the thickness of the teeth vary, the two images will overlap by different amounts as successive teeth are brought into view under the microscope, with the result that the point of intersection P will move towards or away from the crests of the teeth.

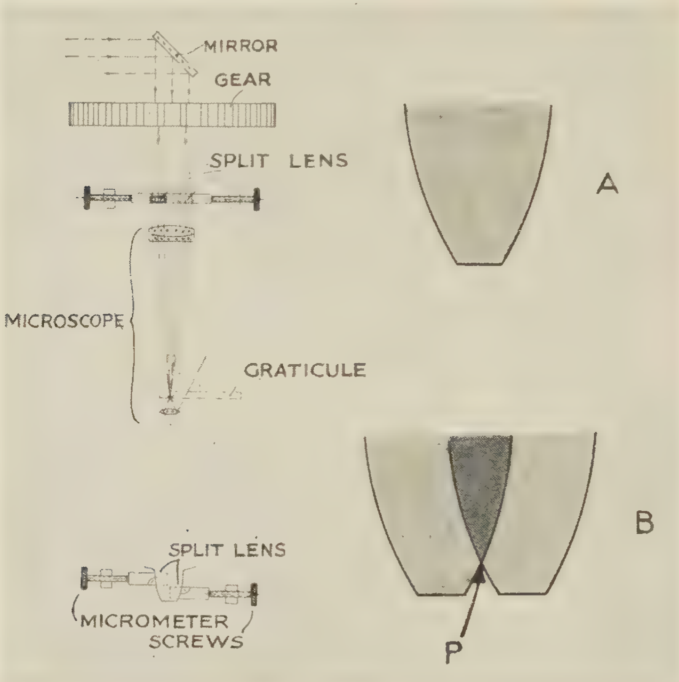


Fig. 321.

In order to detect and measure such variations, the eyepiece of the microscope is fitted with a special graticule ruled with a variety of lines, as in Fig. 322. The extent of the field covered by the eyepiece is indicated by the two smaller circles, but any portion of the graticule can be brought into view by revolving it about its centre, which is eccentric with respect to the axis of the microscope.

Two schemes are employed for testing the equality of thickness of the teeth. In the first, use is made of the two eccentric circular arcs in the region A of the graticule. By rotating the latter, the distance separating the two curves at the centre of the field can be set to correspond with any specified tolerance in the thickness. The point of intersection of the overlapping images is then adjusted, as at I in Fig. 323, so as to fall suitably within the space between the two curves, after which, by rotating the gear, tooth by tooth, it can be seen whether the point wanders beyond the boundaries, as indicated by Diagram II of the same figure.

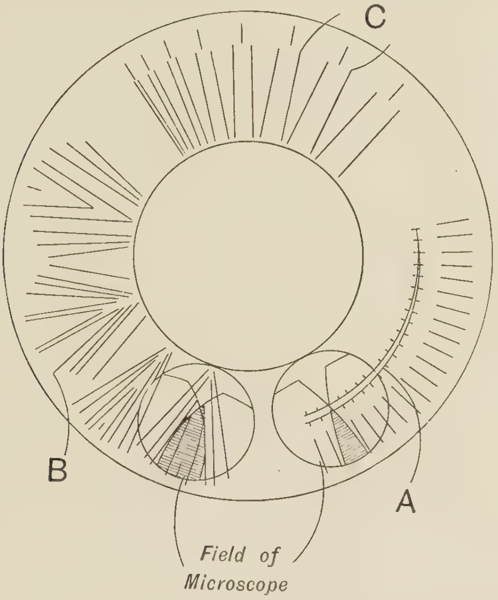


Fig. 322.

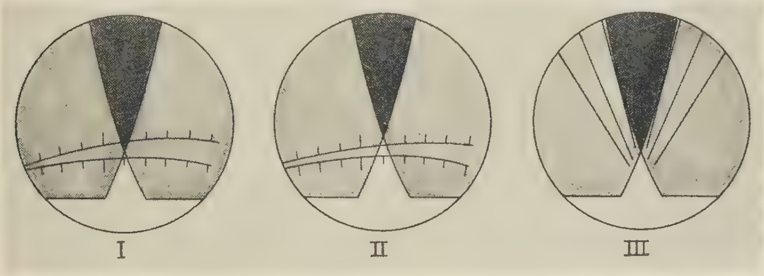


Fig. 323.

In the second method, the width of the overlapping region is adjusted by the lens micrometers so as just to make contact on each side with a pair of inclined lines, as at III in Fig. 323. Various sets of these lines to suit different sizes of teeth are shown at B in Fig. 322. The gear is then rotated and micrometer settings are made for each successive tooth. The degree of uniformity in the tooth thickness is then readily found from the series of readings obtained.

Errors in the symmetry of the teeth can be detected by noting whether the point of intersection of the profiles travels along a radial line as the settings of the two lens-micrometers are altered by equal amounts. Should an error be present, its magnitude can be determined by comparison with the distances separating various pairs of parallel lines on the graticule. These are shown at C, Fig. 322.

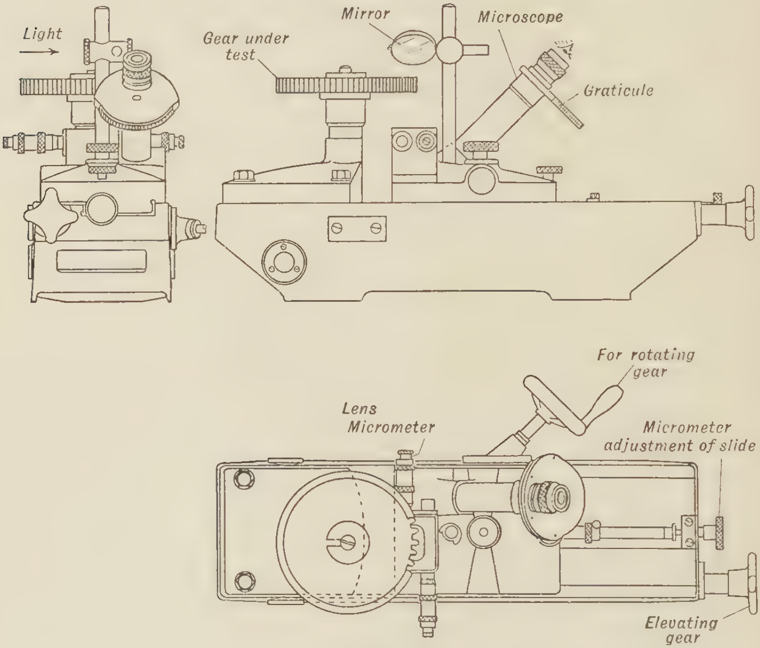


Fig. 324.

Diagrams of the actual machine, which will accommodate spur gears up to a diameter of 16 inches, are given in Fig. 324.

In order to obtain clearly defined images in the microscope, the optical system has to be focussed upon either the upper or the lower face of the gear. The accuracy of the measurements by this instrument would therefore appear to depend upon the crispness of the ends of the teeth at the surface under observation.

It need hardly be pointed out that measurements of variations of tooth thickness round a gear cannot necessarily be taken as a criterion of the uniformity of pitch of the teeth. Only when the method of cutting produces exact equality in the widths of the intervening spaces do errors in pitch produce corresponding variations in tooth thickness. Since the methods described above for testing the thickness of the teeth can be applied equally well to the spaces, it is possible, by suitably combining sets of measurements upon the teeth and spaces, to obtain the variations in the pitch of the teeth.

If the micrometers used for separating the two halves of the split lens have sufficient range, it should be possible, by setting the images of consecutive teeth to overlap each other almost entirely as in Fig. 325, to check the accuracy of pitch of each set of flanks individually. As each pair of teeth is brought in turn into the field of view by rotating the gear, the micrometers could be adjusted so as to bring corresponding flanks of the teeth, such as *ab* and *ef*, tangential to a suitable pair of parallel lines A, on the graticule. Variations in pitch from flank to flank would then be indicated by alterations in the separation of the half-lenses, as given by the micrometer readings. A similar pair of fiducial lines B would be required for testing the opposite flanks, *cd* and *gh*.

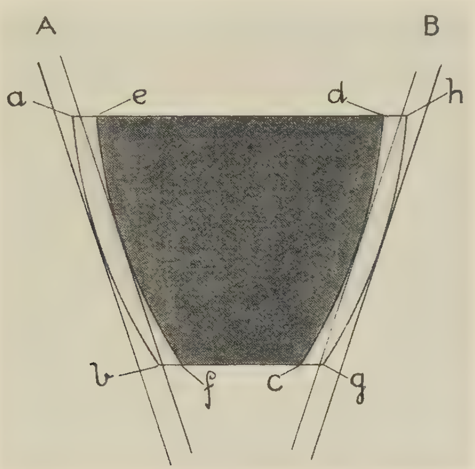


Fig. 325.

Wickman Gear-Measuring Machine.

This machine provides a means of measuring the uniformity of spacing of the teeth round a gear and their concentricity with respect to the axis of rotation. The machine is automatic in action and produces a printed record of the errors of each tooth, or rather the spaces between the teeth.

The principle of the machine is quite simple. Of two ball-ended stylus which engage in neighbouring spaces between the teeth of the gear to be tested (Fig. 326), the left-hand one is capable only of a radial movement, whilst the other can move both radially and tangentially. The gear is rotated tooth by tooth, each space being occupied and positioned in turn by the locating stylus. At each position, the right-hand indicating stylus is brought into engagement with the neighbouring space and, by means of a dual-purpose indicating device, it records variations both in the distances between consecutive spaces and the concentricity of the spaces with respect to the axis of rotation.

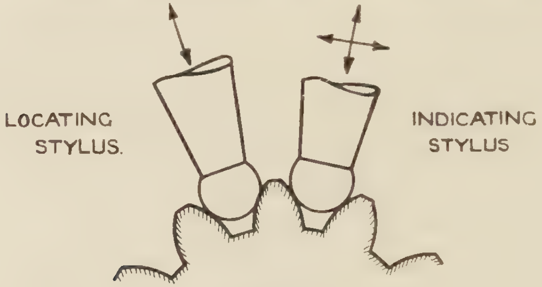


Fig. 326.

A diagrammatic arrangement of the indicating mechanism is shown in Fig. 327.* The spherical-ended locating stylus A is attached to a hinged plate anchored at the top, and is capable of movement only in a direction parallel to PQ. The indicating stylus B is supported on another flexible steel strip, anchored at the bottom. This strip can not only bend backwards and forwards but also twist, so that the stylus is capable of movements in the two directions, PQ and RS, which are respectively radial and tangential with respect to the gear under test.

With the gear locked in position by inserting the stylus A between two of its teeth, the indicating stylus B in the next space will be deflected from its resting position through certain distances in the two directions. It is clear that, for a defective gear, these distances will vary as the two stylus come into contact with successive pairs of spaces, in turn. The variations in the radial and tangential positions of the indicating stylus are enlarged and recorded in the following manner. The radial displacements (parallel to PQ) cause endwise movements of the rod C, which are communicated by the abutment D to the short arm of a second lever E, causing its supporting strip to twist about a vertical axis and giving rise to increased transverse movements at the other end F, of this lever. Still further magnification is obtained by another lever G, the short arm of which is connected to F by a double-pointed strut H, held in position by a pair of tension springs. This last lever, which is furnished at the tip with a marking point, is mounted on an arrangement of crossed strips* so as to be capable of rotation about a virtual axis I.

---

* Reproduced from *The Engineer*, vol. 138, p. 272 (1924), by courtesy of the Editor.

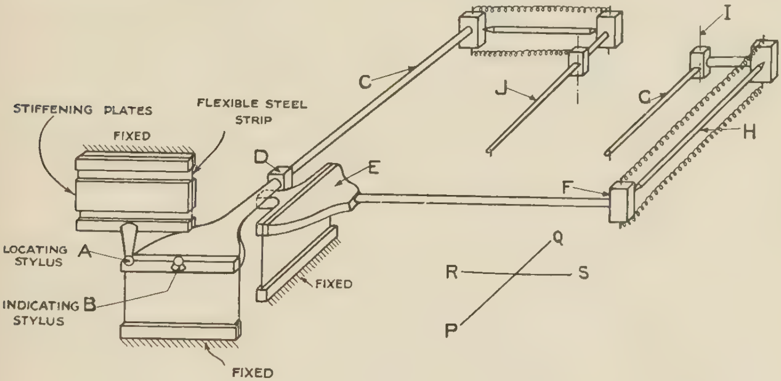


Fig. 327.

Returning to the indicating stylus B, its displacements tangential to the gear wheel (parallel to RS) cause the supporting strip to twist and deflect the rear end of the lever C sideways. The deflection is magnified by another lever J, coupled to C by a strut, and supported by a similar crossed-strip arrangement to that at I. The dimensions of both lever systems are such that errors in pitch and concentricity are magnified approximately 300 times.

For each position of the gear with respect to the two indicator points, the errors in concentricity and pitch are recorded by a pair of dots made on a chart of the type shown in Fig. 328. This chart is wound across under the marking points at the ends of the levers G and J (Fig. 327), and for each position a striker arm descends and brings the points into contact with the paper. The scale of vertical lines on the chart represents errors of 0·0005 inch; their distance apart on an actual chart is 0·15 inch.

---

* See p. 281.

In the example given, errors in pitch amounting to ±0·0005 inch are of frequent occurrence, and at the positions marked X abrupt errors of nearly 0·001 inch are revealed. Similarly, the left-hand side of the chart shows the presence of errors in concentricity of rather more than ±0·0005 inch.

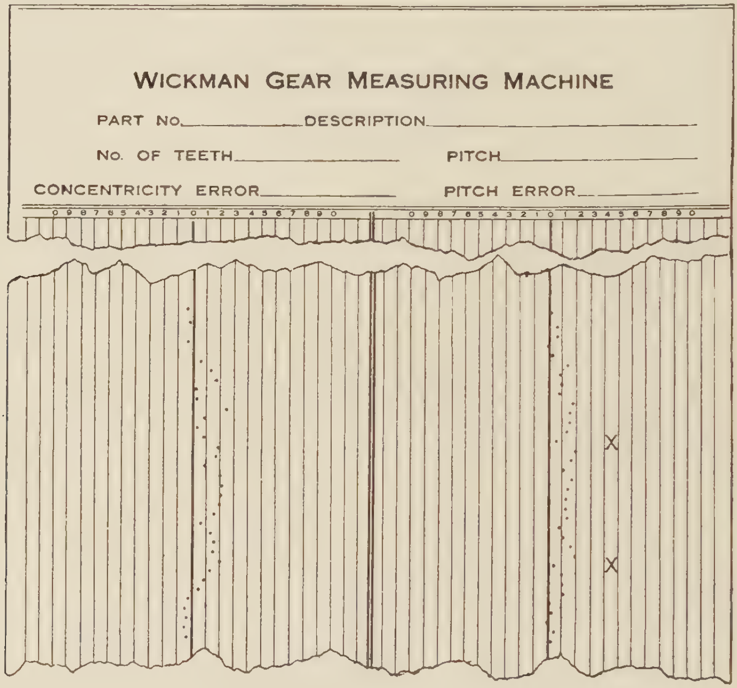


Fig. 328.

The general arrangement of the machine will be gathered from Fig. 329. Essentially, it comprises a column, on the front face of which is mounted a vertical slide, which in turn carries an arbor for supporting the gear under test. The upper face of the column supports two heads, the left-hand one of which carries the locating stylus; the other supports the indicating stylus and recording mechanism. The angular position of the indicator head is adjustable round a horizontal, curved slide in order that the distance between the two ball-ended stylus can be set to suit the pitch of the gear to be examined. In addition, the radial positions of the two heads can be adjusted to suit gears of different diameters.

The operation of the machine is controlled by rotating the star-wheel at the front of the machine. This slowly turns the gear until the latter becomes locked in position by the locating stylus. The indicating stylus then takes up its position in the next space, and dots are marked on the chart. Further rotation of the wheel withdraws both stylus and turns the gear until the next space is indexed, and so on throughout the whole circumference of the gear.

It may be mentioned that the stylus points need not always be inserted in adjacent spaces in a gear, but may be set, if desired, so as to cover more than one pitch. The size of the balls fitted to the stylus holders is chosen to suit the particular pitch of the gear to be examined so that contact is made in the neighbourhood of the pitch line.

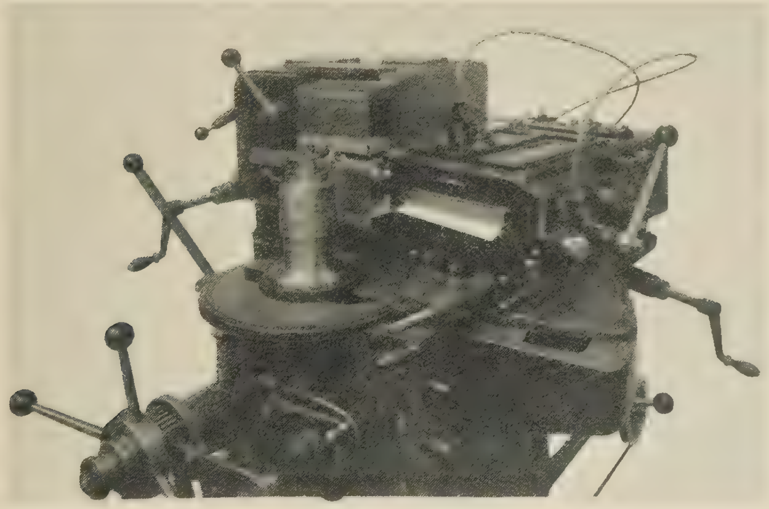


FIG. 329.

The measurements of pitch obtained on such a machine obviously relate to the centres of the spaces between the teeth, and are of little value if one requires to know the accuracy of pitch of the two sets of flanks independently. It is hardly necessary to point out that, with gears as ordinarily used, accuracy of form and pitch is really essential only on the driving flanks of the teeth, the opposite flanks being rendered ineffective by the usual clearance allowed.

ADDITIONAL REFERENCES FOR CHAPTER XV

“Saurer Bevel Gear Testing Machine,” *Engineering*, vol. 113, p. 228 (1922).

“Machine for Measuring Gear Teeth” (Messrs. Vickers), *Engineering*, vol. 114, p. 410 (1922).

“S.G. Gear Measuring Machine,” *Machinery*, vol. 24, p. 831 (1924).

“Gear Testing Machines” (Parkinson and Sons), *Machinery*, vol. 24, p. 729 (1924).

“Wickman Gear Measuring Machine,” *The Engineer*, vol. 138, p. 272 (1924).

“Sykes Gear Lapping and Testing Machine,” *Amer. Mach.*, vol. 63, p. 1075 (1925).

“Automatic Gear Tester,” *Amer. Mach.*, vol. 69, p. 104 E (1928).

“Gear Checking Machine,” *Amer. Mach.*, vol. 69, p. 6 E (1928).

Zahnrad-Messungen, Dr. G. Berndt (published by Gebr. Richters, 1925).

“The Sykes Gear Tooth Comparator,” *Engineering*, vol. 112, p. 103 (1921).

“The Odontometer for Testing Gear Teeth,” *Machinery*, vol. 18. p. 412 (1921).

“Machine Tool Patents. Testing the Accuracy of Teeth of Bevel Gears” (Messrs. Saurer), *Machinery*, vol. 18, p. 717 (1921).

“Van West Gear Tooth Testing Appliance,” *Engineering*, vol. 115, p. 74 (1923).

“Hartness Modified Screw Thread Comparator for Testing Gears,” *Machinery*, vol. 22, p. 81 (1923).

“Gear Measuring Equipment,” Maag, *Machinery*, vol. 28, p. 301 (1926).

“Sykes Gear Tooth Comparator,” *Amer. Mach.*, vol. 63, p. 1070 (1925).

“Zeiss Involute Gear Tester,” *Machinery*, vol. 29, p. 838 (1927).

“Gauging Involute Threads,” H. E. Merritt, *Machinery*, vol. 22, pp. 11, 79, 191, 210, 251, 275, 307, 376, 475, 525, 569 (1923).

“Illinois Universal Hob and Worm Testing Machine,” *Amer. Mach.*, vol. 68, p. 1068 (1928).

“Gear Tooth Measuring Instrument,” *Amer. Mach.*, vol. 63, p. 158 E (1925).

“Measuring Gear Teeth,” J. L. Williamson, *Amer. Mach.*, vol. 63, p. 609 (1925).

“Checking Gears by the Wire Method,” H. G. Thuesen, *Amer. Mach.*, vol. 63, p. 824 (1925).

“Gear Testing Appliances,” *Amer. Mach.*, vol. 53, p. 176 E (1920).

“Modern Problems in Gear Testing and a Proposed Testing Machine,” W. Lewis, *Amer. Mach.*, vol. 59, p. 875 (1923).

“Inspection of Involute Gears and Hobs,” *Machinery*, vol. 19, p. 90 (1921).

“Characteristics and Uses of Ground Gears,” H. F. L. Orcutt, *Proc. Inst. Mech. Eng.*, p. 1159 (1925).

“Machining and Measuring Gear Teeth,” Earle Buckingham, *Amer. Mach.*, vol. 66 pp. 879, 969, 1051 ; vol. 67, pp. 7, 49, 233, 265, 313, 419, 497, 617, 657, 733, (1927).

“New Maag Gear Grinder,” *Amer. Mach.*, vol. 69, p. 91 E (1928); *Machinery*, vol. 32, p. 806 (1928).

“Gear Grinding by Form Wheel,” *Amer. Mach.*, vol. 65, p. 213 E (1926).

“The Design of Gear Tooth Forms,” E. Buckingham (series of articles), *Amer. Mach.*, vols. 64 and 65 (1926).

“Proposed Standard for Spur Gear, Tooth Form,” *Mech. Eng.* (Amer.), vol. 48, p. 1157 (1926).

“Influence of Elasticity on Gear Tooth Loads,” *Mech. Eng.* (Amer.), vol. 48, p. 893 (1926) ; vol. 49, pp. 644, 767, 907, 1228, 1322 (1927) ; vol. 50, pp. 27, 469, 627 (1928).

“Photoelasticity and its Relation to Gear Wheels,” A. L. Kimball, *Amer. Mach.*, vol. 63, pp. 7, 51 (1925).

“Tooth Forms of Green, Burnished, Hardened and Ground Gears,” *Amer. Mach.*, vol. 59, p. 5 (1923).

“S.I.P. Gear Testing Apparatus,” La Société Genevoise Catalogue, No. 458 ; also *Amer. Mach.*, vol. 69, p. 558 (1928).

“The Strength of Gear Teeth,” *Mech. Eng.* (Amer.), vol. 48, p. 1105 (1926).

“Zeiss Gear Testing Appliance,” *Amer. Mach.*, vol. 70, p. 115 E (1929).

CHAPTER XVI

MEASUREMENT OF GEARS (*continued*)

The N.P.L. Gear-Measuring Machine.

TOWARDS the end of the year 1918, attention was directed in the Metrology Department of the National Physical Laboratory towards accurate measurements of the various elements of gears. The results of G. A. Tomlinson's work on the subject, both as regards apparatus which he designed for carrying out measurements on gears of various types and also his theoretical investigations into the effects of different classes of errors upon the running qualities of gears, are to be fully described in a forthcoming volume of the *Collected Researches* of the Laboratory. Limitation of space prevents more than a brief description here of the methods adopted by Tomlinson for dealing with the measurement of gears and hobs.

It may be mentioned that the methods about to be described enable accurate measurements to be made both upon the relative positions and the form of the teeth of all the usual types of gears such as spur, helical, worm, straight-bevel and spiral-bevel. Hobs for cutting gears can also be dealt with in a similar manner. Moreover, in addition to measuring errors of the individual elements of gear teeth, it is possible to obtain autographic records of the interaction of gears when run together.

A general view of the machine with a small spur gear mounted for test is illustrated in Fig. 330. The gear, mounted on a carefully centred arbor, is held between a pair of centres situated towards the back of the machine. The brackets for the centres are fixed to the main bed plate A, which carries two slides. The lower one B is capable of free motion on steel balls in vee-grooves in a direction at right angles to the line of centres. The upper slide C rests on ball bearings on the lower slide B, and can be traversed parallel to the centres. The positions of the two slides are controlled and recorded by accurate micrometer screws D and E respectively.

Originally the upper slide C carried an indicating device F, which took the form of a ball-ended lever capable of vertical movement controlled by a micrometer screw.* To examine the shape of a tooth, the ball point was brought into contact with a succession of points round a tooth, the relative positions of which were read

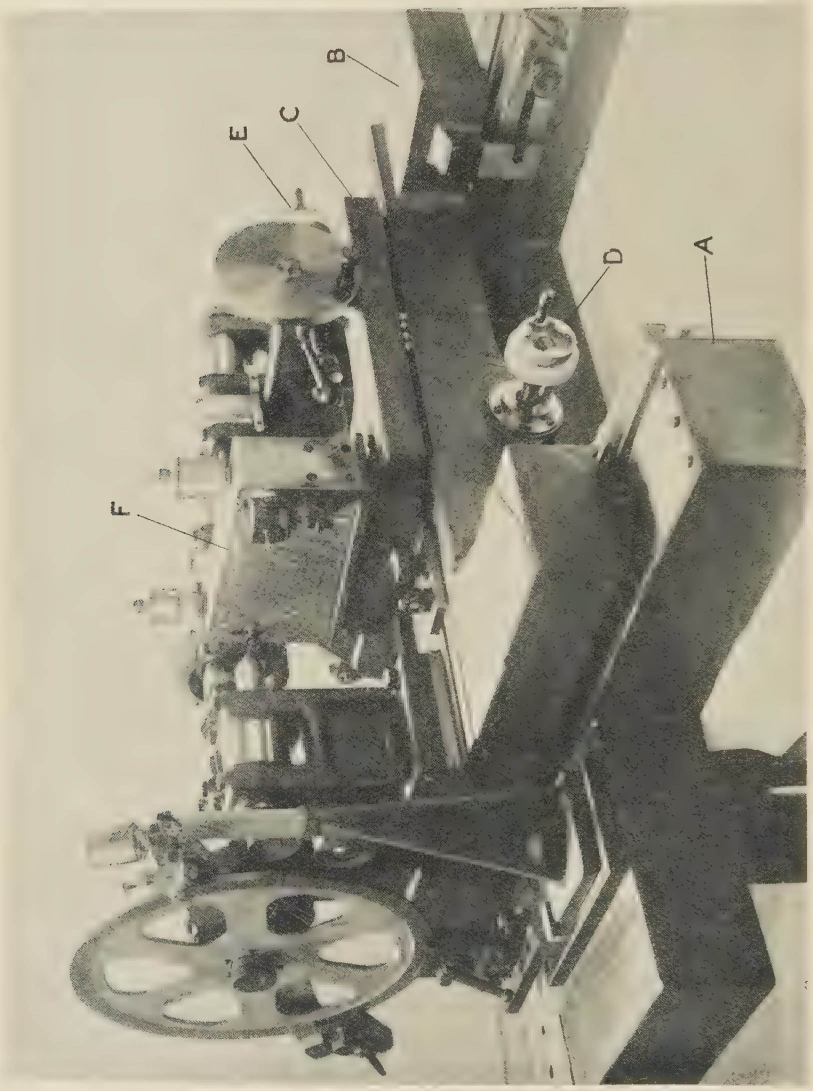


Fig. 330.

---

* For description, see *Engineering*, vol. 116, p. 104 (1923).

in rectangular co-ordinates by the micrometers on the indicator lever and slides of the machine. Errors in pitch were measured on each set of flanks in turn, by taking an indicator reading on each tooth as the gear was rotated accurately through successive increments equal to 360° divided by the number of teeth. (The method used for this angular movement will be described later.)

This form of indication, although very accurate, suffered from the disadvantage that the measurements obtained referred only to isolated points on the teeth. The method has since been discarded in favour of a pantograph mechanism, by means of which it is possible to record the shape and relative position of any tooth brought in front of the tracing point of the mechanism.

(*a*) *Pantograph.*—The design of the pantograph, which was required to copy the shape of a tooth accurately to within 0·0001 inch, involved an investigation into the general theory of such mechanisms, including a study of the effect of possible errors in workmanship upon the truth of the copy produced.

As regards the type of linkwork to be used, choice could be made from amongst a wide variety of forms. With two pairs of parallels hinged at A, B, C and D, as in Fig. 331, a pantograph mechanism can be obtained by drawing a line intersecting them and choosing any three of the four points of intersection as the tracing, scribing and fixed points. For the usual types of pantograph a line, such as PQ or RS, is chosen so as to pass through one or other of the hinges, but the mechanical difficulty arising from a double pivot at D rendered such forms undesirable. For the purpose in view, a line such as LM was chosen, the fixed pivot O bisecting the link

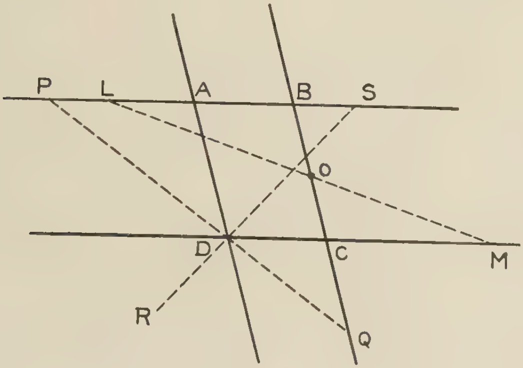


FIG. 331.

BC, and L and M being the tracing and scribing points. Tomlinson also found that this particular form of the mechanism had the additional advantage that it permitted of a simple adjustment for the position of the scribing point so as to obtain a true copy.

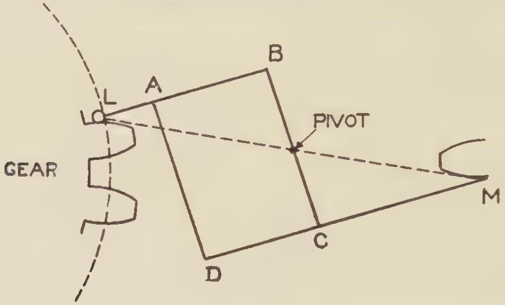


FIG. 332.

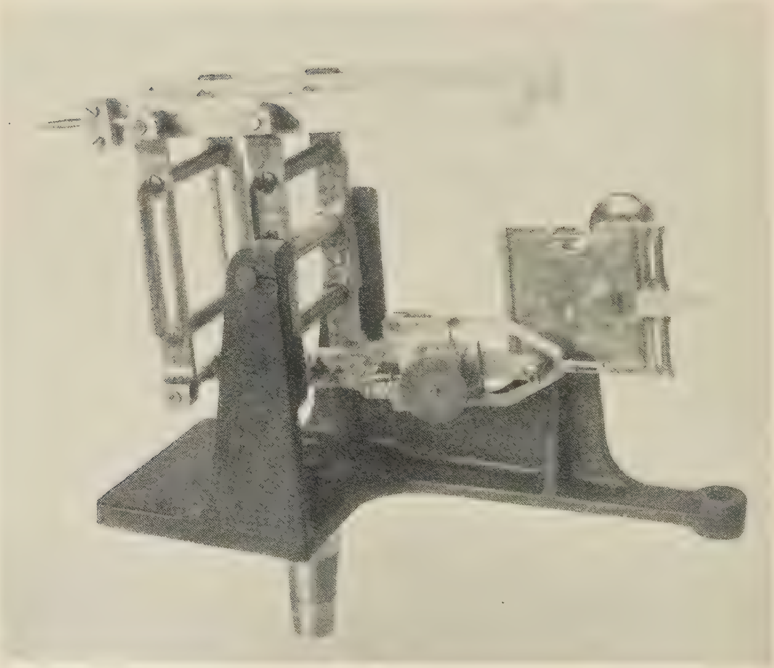


FIG. 333.

An outline of the pantograph mechanism used is shown in Fig. 332, the actual instrument being illustrated in Fig. 333. The tracing point is provided with a small steel ball, which is carried round the profile to be reproduced, the record being scribed on a smoked-glass plate by a specially fine steel point supported on two parallel steel strips about 0·001 inch thick. The resulting light contact enables a line to be produced only 0·0002 inch wide. The pivots for the linkwork consist of four pairs of hardened, 60°-cones fitting into small conical holes. The accuracy of the linkwork of the parallelogram can be readily checked by direct measurement, whilst the position of the scribing point can be easily adjusted after trial. The complete mechanism is accurately balanced so as to be in equilibrium in all its possible shapes.

The dimensions of the pantograph are such that the record produced is exactly full size. It is examined and measured after being magnified fifty times in a horizontal projection apparatus.*

When comparing the projected outline with an enlarged diagram of the theoretical shape, it is of course necessary to allow for the size of the small steel ball at the tracing point.

(*b*) *Method of Measuring Pitch.*—Before entering into details of the method used for testing the uniformity of pitch round a gear, reference must be made to the scheme adopted for turning a gear accurately through any given angle.

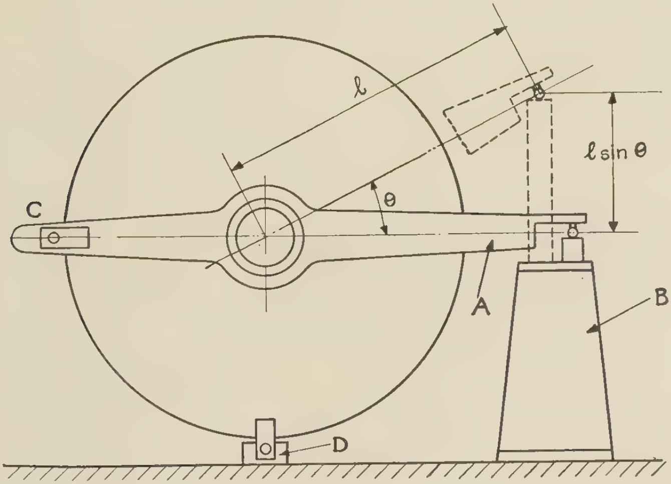


Fig. 334.

The large bronze wheel to be seen at the left of Fig. 330, is directly coupled to the arbor supporting the gear under test. The boss of this wheel forms a bearing for a long steel arm A, Fig. 334, known as the sine plate, which carries a steel ball at its right-hand end at a known radius (about 10 inches) from the centre of rotation. In its initial position the sine plate is horizontal, with the ball resting upon a pile of block gauges supported on a pillar B, the height of the centre of the ball above the base of the machine being exactly equal to that of the axis of rotation. In this position the sine plate and wheel are coupled together by a clamp C. To rotate the gear through an angle θ, the ball is raised so as to rest upon another pile of block gauges differing in length from the first pile by an amount equal to $l \sin \theta$, l being the radius to the centre of the ball. To repeat the angular displacement, the wheel is held rigidly by clamping it to the base of the machine at D, after which the sine plate is freed at C and returned to its initial horizontal position, with its ball resting on the original pile of gauges. By tightening the clamp C, releasing D and inserting the larger pile of gauges under the ball, the gear can be rotated once more through the same angle θ, and so on as often as is desired.

---

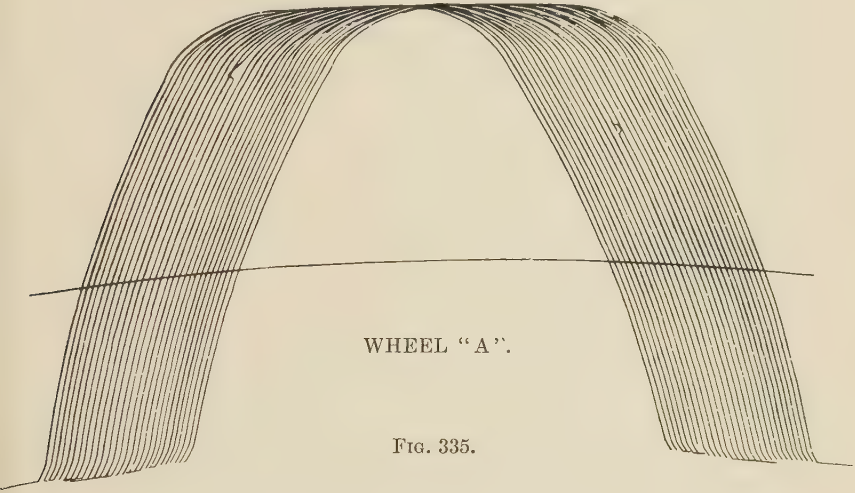
* See pp. 229 and 233.

The accuracy to which the angular movement is repeated depends largely upon the proper functioning of the two clamps. These were specially designed, so that, in the action of gripping the wheel, pressure is applied quite normally to the sides, there being no tendency to turn it about its axis.

The scheme just described for rotating the gear successively through a given angle forms the basis of the method of testing the uniformity of pitch round a gear. With the sine plate in its horizontal position, a record is obtained of a tooth on the pantograph plate. The gear is then rotated through an angle equal to the angular pitch plus or minus a small amount, so as to bring the next tooth into a position slightly to one side of that previously occupied by the first. The object of the small difference is to cause the record of the second tooth on the smoked plate to be displaced slightly from that of the first. By rotating the gear time after time through the same angle, every tooth is brought in succession before the scribing ball of the pantograph and its record is traced on the plate. In this manner, a diagram is obtained of all the teeth round the gear artificially compressed into the space of about one tooth, the actual pitch being reduced to a small amount of the order of 0·003 inch.

It will be readily understood that by projecting such a group record of the teeth to a magnification of, say, fifty times, a lack of uniformity of the pitch of the order of only 0·0001 inch is immediately revealed by a noticeable irregularity in the spacing of the flanks in the enlarged image.

The method has several advantages over and above the fact that the group record enables a rapid examination to be made of the form and relative position of every tooth round the gear. For example, the correctness of the spacing of the teeth can be judged from their complete profiles rather than from measurements, as often obtained, at isolated points on the flanks; the pitch of each set of flanks is tested quite independently; further, it so happens that abrupt changes in the pitch, which are more detrimental to smooth running than those of a progressive character, are those most readily discernible from the record. Finally, a group diagram of the teeth provides a permanent record, and, if desired, can be reproduced photographically.



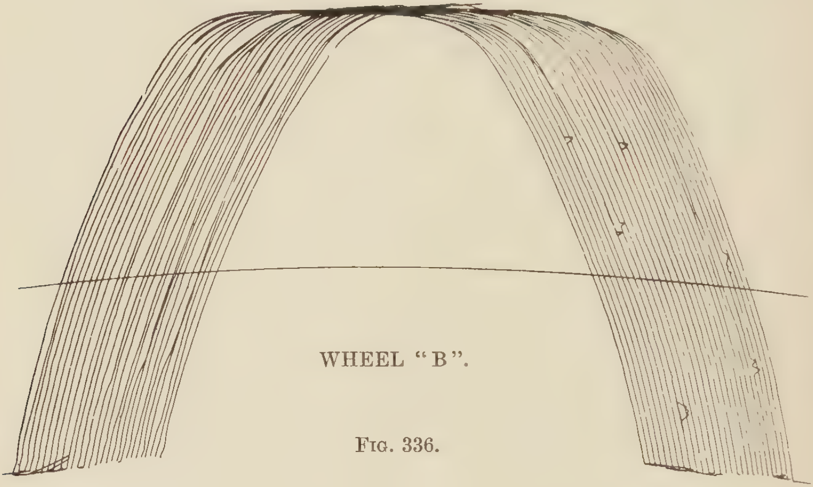
WHEEL "A".

Fig. 335.

Two examples of such group records, at a magnification of ten times, are shown in Figs. 335 and 336. These charts were taken from two similar helical gears having twenty-seven teeth, and a pitch circle of 3·3 inches diameter. From these diagrams it is obvious that the spacing of the teeth of the first gear is much more uniform than that of the second. In addition, whilst both sets of flanks of "A" appear equally good, the right-hand flanks of "B" are much better spaced than the opposite ones.

The actual cumulative pitch errors of each set of flanks, as obtained from these diagrams, are shown in Fig. 337. The two curves for gear "A" are fairly regular in character, and indicate periodic errors of range 0·002 and 0·003 inch on the two sets of flanks. The difference between the two sets of flanks of the other gear is made evident by the two lower curves, the one for the left-hand flanks being particularly erratic. In addition to local irregularities, both curves reveal periodic errors in the pitch, having ranges of about 0·003 and 0·005 inch for the two sets of flanks.

The variations in tooth thickness round the pitch circle, as obtained from the pitch curves of the two sets of flanks, are shown in Fig. 338. Here again it is obvious that, in gear " B ", the variations are not only greater but also more erratic. The general resemblance of the two curves to a sine curve shows that the lack of uniformity in tooth thickness might be due to eccentricity of the teeth with respect to the axis of the gear. The periodic error in the cumulative pitch might also be due to the same cause.



WHEEL "B".

Fig. 336.

It may be mentioned that the effect of such periodic variation in cumulative pitch round a gear is to cause a small rhythmic fluctuation in speed, recurring every revolution, which is not likely to be serious, except perhaps at high speeds. Local variations in pitch from tooth to tooth, giving rise to sudden changes in the speed, are much more detrimental to the smoothness of running of a gear.

This is very well illustrated in the case of the two gears referred to above. Fig. 339 gives the variations in circular pitch from tooth to tooth for each set of flanks of both gears. The maximum variation in the case of gear " A " is of the order of ±0·0005 inch ; the right-hand flanks of gear " B " show variations of ±0·001 inch, whilst the opposite flanks show errors of about double that amount. This

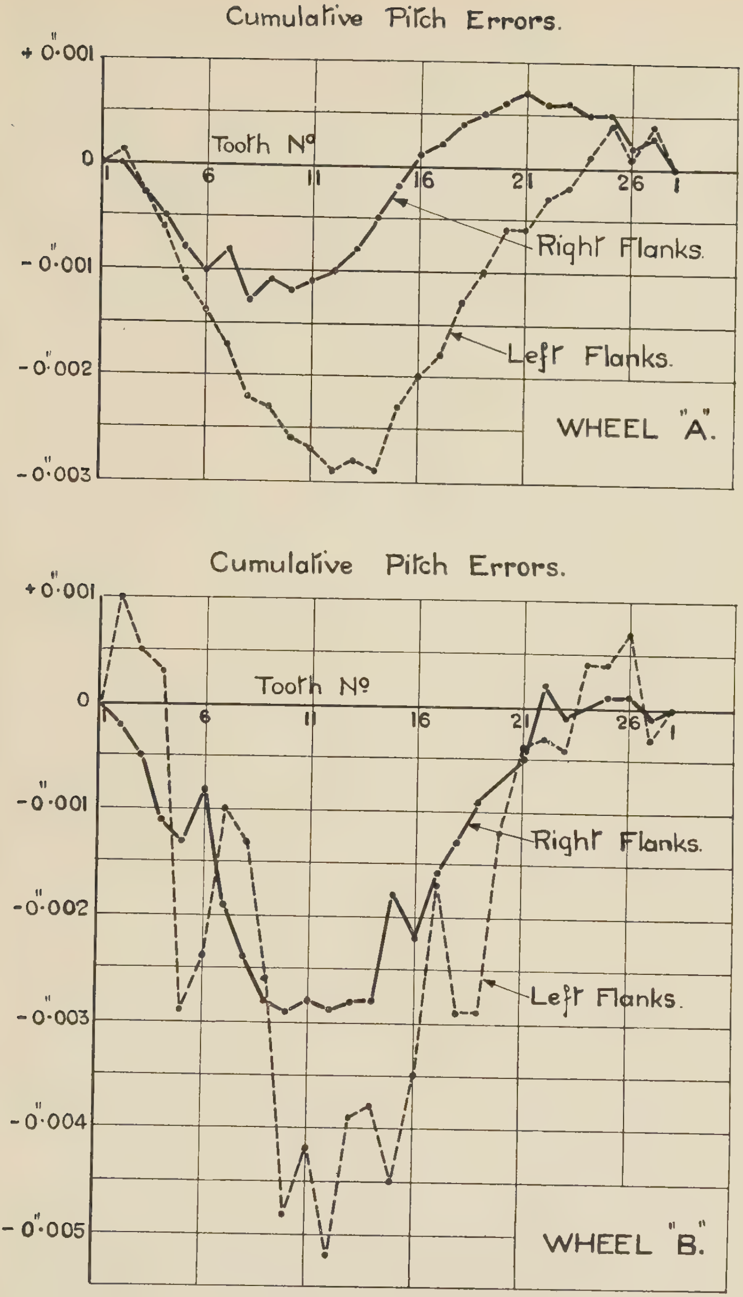

Cumulative Pitch Errors.
+ 0·001"
0
- 0·001"
- 0·002"
- 0·003"
Tooth No
1
6
11
16
21
26
1
Right Flanks.
Left Flanks.
WHEEL "A".
Cumulative Pitch Errors.
+ 0·001"
0
- 0·001"
- 0·002"
- 0·003"
- 0·004"
- 0·005"
Tooth No
1
6
11
16
21
26
1
Right Flanks.
Left Flanks.
WHEEL "B."

Fig. 337.

explains fully why gear "A" was reported to run much quieter than the other.

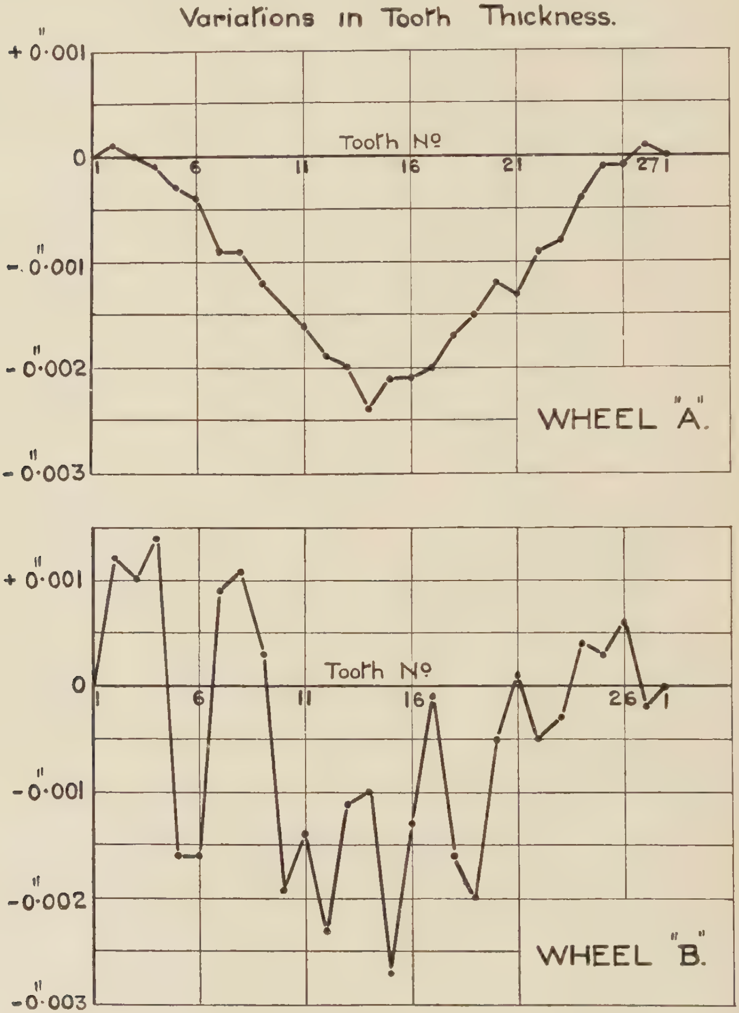


Fig. 338.

(c) *Radial Alignment of Teeth.*—Before dealing with the method used for checking the shape of gear teeth, reference may be made to the scheme for testing their radial and axial alignments. A gear in which the centre lines of the teeth do not pass through the axis will, even though the teeth be correctly shaped, run as though an error in pitch occurred at every tooth. A sudden change of speed will, therefore, occur every time a tooth comes into or goes out of engagement, with consequent harshness of running.

To check the squareness of a tooth, two pantograph records of

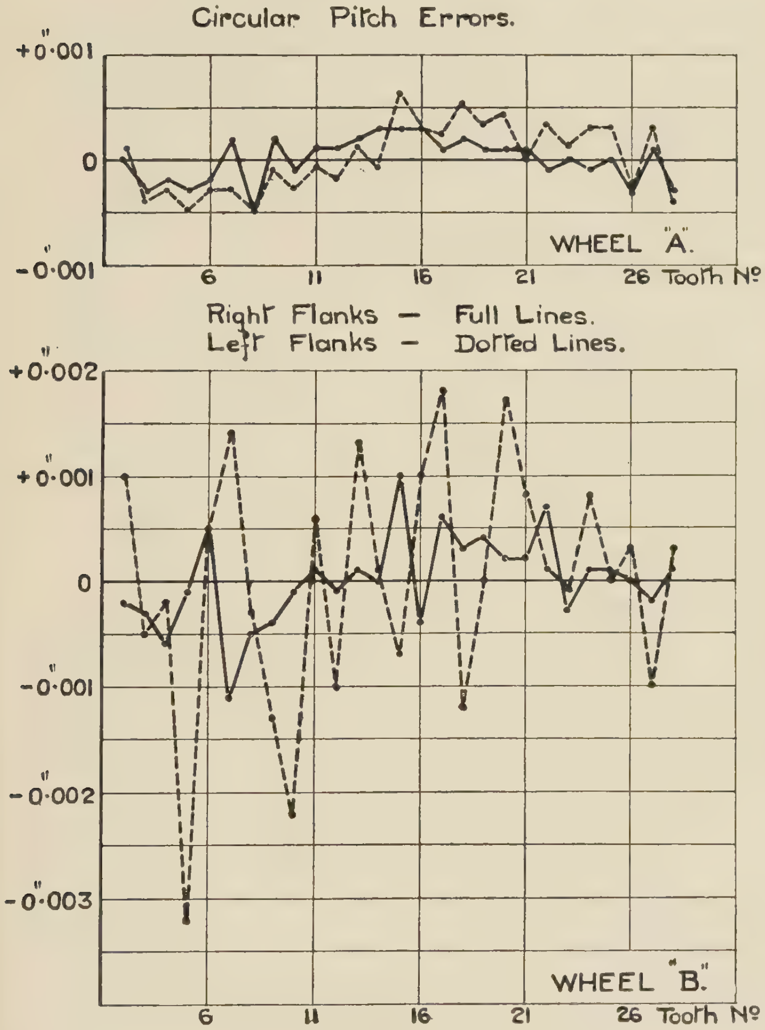


Fig. 339.

it are taken on the same plate, one before and the other after reversing the wheel on the centres of the machine. Should the two records appear as in Fig. 340, it is obvious that the centre line of the tooth is not true with the axis of the gear. The error, which is of course doubled by the process of reversal, can be readily measured on the screen of a projection apparatus.

The same result can be derived from a single record of a tooth which bears, in addition, a trace of an arc of a circle obtained by scribing round a portion of the circumference of a plug gauge of suitable size, placed on the centres of the machine. The symmetry of the two flanks with respect to the arc can be tested by projecting the record and comparing the image on the screen with that obtained after turning the smoked-plate face for face.

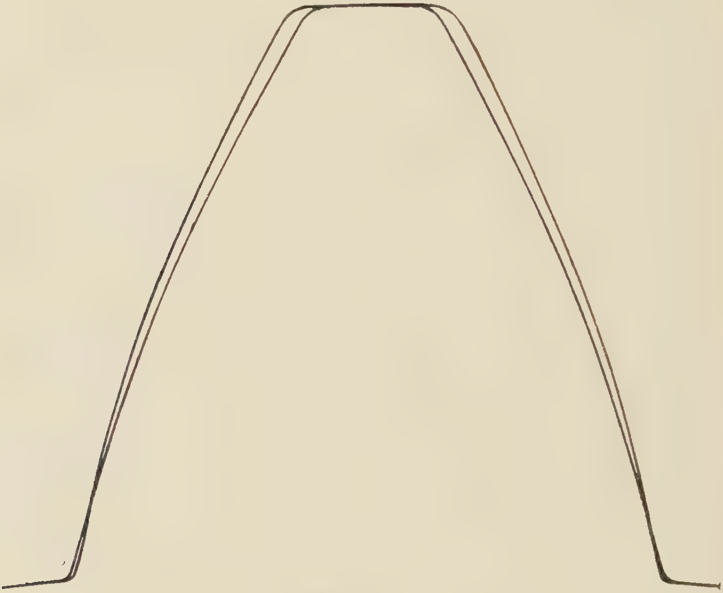


Fig. 340.

(*d*) *Parallelism of Teeth of Spur Gear to Axis.*—Should the teeth of a spur gear not be parallel to the axis, the load will tend to become concentrated towards one end of the teeth. It is important, therefore, to examine gears for axial alignment of the teeth.

The test is made at four positions round a gear by taking a series of pantograph records at equally spaced intervals along a tooth, the gear being rotated through a small constant angle between each successive trace. The resulting group diagrams are examined by projection, and from measurements of the spacings it is possible not only to find the amount of error present in straightness and axial alignment of the teeth, but also to state whether it is due to faulty alignment of the cutter stroke, or to the gear being mounted slightly askew on the arbor during cutting.

(*e*) *Shape of Teeth and Base Circle Diameter.*—The simplest method of examining the accuracy of the shape of the tooth is to compare the projected image of its pantograph record with a line-drawing of the nominal outline enlarged fifty times. Each flank can be examined in turn, and departures from true form measured with a scale. To make the comparison, it is necessary that the record of the tooth should be crossed by a circular arc formed by tracing a portion of the circumference of a suitable cylindrical plug of known radius, which is substituted for the gear on the centres of the machine.

When making a comparison with the nominal involute, it often happens that the actual profile shows errors which vary progressively from the base to the top of the tooth, indicating an error in the diameter of the base circle. In such cases, instead of drawing a number of involutes with slightly varying base circles to compare with the profile, it is preferable to adopt the following geometrical method, devised by Tomlinson, for determining the diameter of the base circle from the profile.

In Fig. 341, PG represents one flank of the tooth intersected at P by a datum circle of known radius. A and B are points on this circle equidistant from P. A normal PH is drawn by trial to the profile at P cutting the chord AB in F at an angle a.

From a measurement of the angle a and the known radius of the datum circle, it is then possible to calculate the required radius of the base circle.

Let C be the centre of the required base circle HG, of radius b,

r = radius PC of the datum circle,
θ = angle GCH,
ϕ = angle PCG.

Then, since angle PCH $= a$,

$$\theta = a + \phi. \qquad (1)$$

We have,

$$\begin{aligned} r^2 &= \mathrm{PH}^2 + \mathrm{CH}^2 \\ &= (b\theta)^2 + b^2 ; \end{aligned}$$

$$\therefore\ b^2 = \frac{r^2}{1+\theta^2} \qquad (2)$$

Draw PJ perpendicular to CG produced.

Then from the geometry of the figure,

$$\mathrm{PJ} = b \sin\theta - b\,\theta.\cos\theta.$$

Also,

$$\sin\phi = \frac{PJ}{PC} = \frac{b(\sin\theta - \theta . \cos\theta)}{b\sqrt{1+\theta^2}}$$

$$= \frac{\sin\theta - \theta . \cos\theta}{\sqrt{1+\theta^2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

It will be seen, therefore, that ϕ is independent of b and is determined by θ.

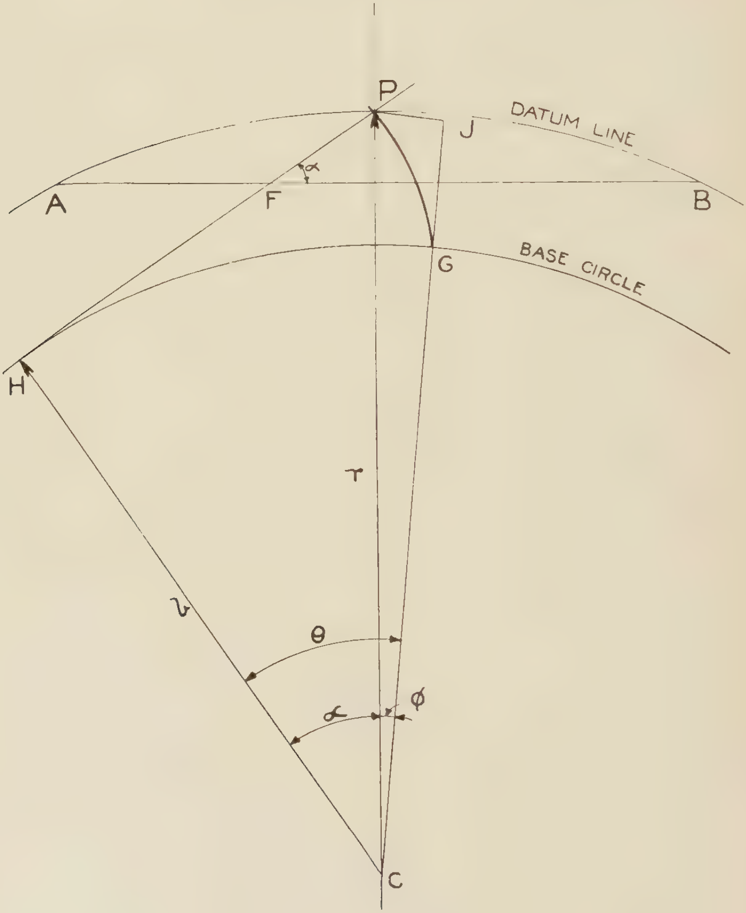


Fig. 341.

Before the radius b can be obtained from equation (2) above, it is necessary to know the value of θ corresponding to the measured value of a.

From equations (1) and (3) we have

$$\sin(\theta - a) = \frac{\sin\theta - \theta\,.\,\cos\theta}{\sqrt{1+\theta^2}}.$$

By means of this relationship, a curve can be plotted between θ and a, and this curve can then be used to ascertain the value of θ corresponding to any particular measured value of the angle a.

Knowing θ, b is readily obtained from equation (2).

The accuracy to which it is possible to obtain the radius b of the base circle depends largely upon the accuracy with which the line PF can be drawn normal to the involute. As a result of experiments made at the screen of the projection apparatus, Tomlinson found that the error in ascertaining the angle a was of the order of only ±0·03°—an uncertainty which would give rise to one of about ±0·0005 inch in the measured value for the base-circle radius of a gear of 6 inches diameter.

It is to be noted that, from a pantograph record of a tooth, it is possible by this method to measure the base circle independently for each flank.

If, instead of one datum circle, several are scribed so as to intersect the profile at fairly regular intervals down the flanks, it is possible to obtain a measure of the base-circle diameter at each intersection and thus obtain some check upon the accuracy of the involute.

An alternative method may be used in cases where it has been proved that the two flanks are symmetrical. Using a pantograph record of the tooth traversed by a series of datum circles of known radii, measurements are made on the projection apparatus of the lengths of the various chords, *ab*, *cd*, etc. (Fig. 342), intercepted by the flanks of the tooth. From these lengths and the radii of the corresponding datum circles it is a simple matter to calculate the angle β subtended by each chord at the centre. Using these values of β and the relationship

$$\phi = \frac{\gamma}{2} - \frac{\beta}{2},$$

where γ is the angle subtended in Fig. 342 by the arc of the smallest datum circle intercepted by the flanks of the tooth, a series of actual values of the angle ϕ can be obtained for each of the other datum circles.

Now, from equation (2) on page 323, we have

$$\frac{r}{b} = \sqrt{(1+\theta^2)},$$

where r is the radius to a given point on an involute of a base circle of radius b, and θ is the angle shown in Fig. 341. By dividing each of the radii of the datum circles by the nominal radius of the base circle of the gear under test, a series of values of θ can be calculated which will correspond with each of the points of intersection. Equation (3) on page 324 is then used to calculate a series of corresponding nominal values of the angle ϕ (Figs. 341 and 342).

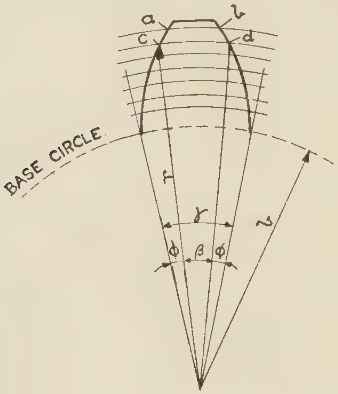


FIG. 342.

The differences between the two series of ϕ, one derived from measurements of the tooth, and the other calculated for a true involute, give the relative errors in ϕ at the radii of the various datum circles, for the tooth under test. These errors can be converted into circumferential errors by multiplying each by the corresponding radius.

(*f*) *Helical Gears.*—Just as in a spur gear it is important from the point of view of satisfactory distribution of load that the teeth should be straight and parallel to the axis, so in the case of helical gears attention should be paid to the accuracy of the helix angle of the teeth.

The method of testing this angle follows that described on page 322 in connection with the axial alignment of the teeth of a spur gear. A succession of pantograph records are made at equal intervals along the tooth, the gear being rotated between each trace through an angle differing by a definite small amount from that corresponding to the nominal helix angle and the amount of traverse. The resulting group record is examined, as usual, by optical projection, and the accuracy of the helix angle obtained from measurements of the spacing of the records. Each set of flanks can be dealt with separately, and variations in tooth thickness along the helix can be readily found.

The other elements of helical gears can be dealt with in a similar manner to that described for spur gears. It is necessary, however, in obtaining the tooth shape from the pantograph record to allow for the fact that the contact between the ball of the pantograph and a helical tooth does not take place in the plane of measurement. The actual shape of the tooth can be obtained from the projected image of the record by drawing a number of circles with their centres on the profile and with radii equal to that of the pantograph ball multiplied by the secant of the actual helix angle of the gear at the various positions occupied by the centres. The inner envelope of the circles gives the required outline.

(*g*) *Bevel Gears.*—The spacing errors of bevel gears are determined from group diagrams similar to those used for spur gears. It should be mentioned, however, that when dealing with a bevel gear, the plane of the pantograph has to be rotated about a vertical axis so as to be normal to the pitch cone of the gear.

In applying the pantograph to the examination of the form of bevel teeth, Tomlinson made an investigation as to errors arising from the fact that the contact of the pantograph ball does not take place truly in the plane of measurement. The case is not so simple as that of a helical gear mentioned above, but he was finally able to show that no appreciable distortion of the tooth form took place, and that it can be obtained with sufficient accuracy from the pantograph record, as in the case of a helical gear.

In order to test the rate of taper, the uniformity of taper and the alignment of the teeth of a bevel gear relative to a generator of the pitch cone, a series of pantograph records are taken at equal intervals along a tooth, the pantograph being translated the required distance on each occasion by suitable component movements of the two micrometers on the gear machine (Fig. 330). For this test it is important that the centre line of the tooth under investigation should be horizontal.

An example of a group record obtained in this manner is shown in Fig. 343, the magnification being tenfold. The relationship between the measured spaces between successive profiles gives the required information as to the rate and uniformity of the taper, and the parallelism of the tooth to a generator of the pitch cone.

Similar tests can be made on a spiral bevel wheel, but in this case, before tracing each section, the gear is rotated by the nominal angle required to bring each section on to a common centre line.

The base circle radius of a bevel wheel can be measured by a slight modification of the method described above for spur gears. Datum ellipses, as in Fig. 343, are scribed on the profile records, using cylinders of known radii as before.

(*h*) *Method of Recording Uniformity of Motion transmitted by a Pair of Gears.*—Provision is made on Tomlinson's gear-testing machine for recording the degree of uniformity of motion transmitted by a pair of gears mounted on parallel axes. The larger gear is mounted on the main centres of the machine and the smaller one on a second pair of centres, one of which is on the lower and the other on the upper carriage. The distance between the two pairs of centres is set correctly to suit the gears to be tested, and the three carriages of the machine are then clamped together.

The mechanism used for carrying out the test will be understood from the diagrammatic arrangement, Fig. 344. The smaller gear G_1, when slowly rotated by hand through the reduction gear shown, drives not only the larger gear G_2, but also a disc D_2, which is coupled by a strained steel tape to a similar disc D_1, mounted on an extension of the spindle carrying G_1. The ratio of the diameters of the discs is made equal to that of the two gears, so that, if the motion transmitted by the latter is exactly uniform, the sleeve upon which D_2 is mounted will revolve with no relative angular motion with respect to the spindle carrying the larger gear G_2.

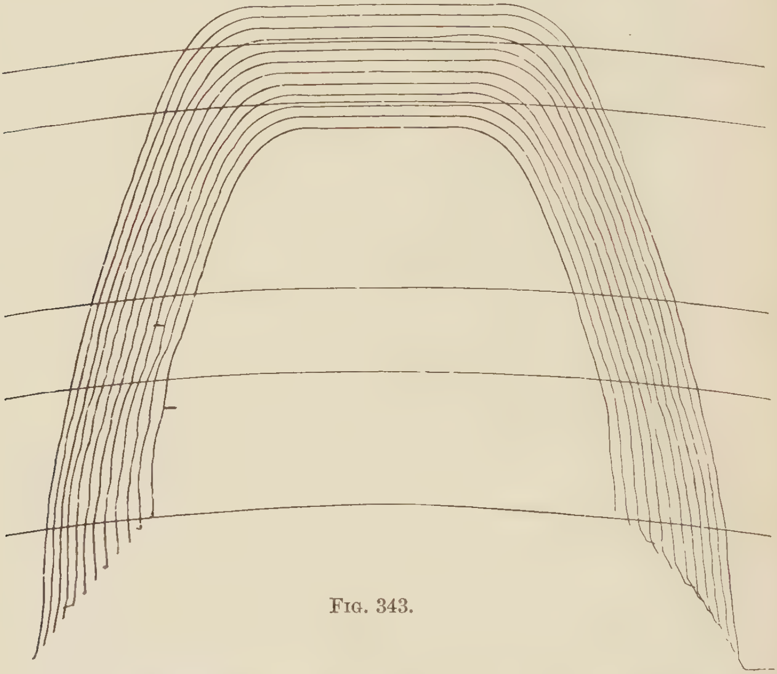


Fig. 343.

In order to magnify and record any relative motion which may occur between G_2 and D_2, the sleeve bearing the disc also carries an arm A, whilst a similar arm B is attached to an extension of the spindle carrying the gear G_2. These two arms are connected at their inner ends by three steel strips, as shown, so that relative angular motion is possible between them. The outer end of arm B is connected flexibly by two pairs of crossed steel strips to a light casting C, which is also coupled to arm A by a single steel strip E. Any relative movement between the two arms will therefore cause an angular movement of the casting C, to which is connected a light arm F, furnished with a steel scribing point H at its other extremity. The effect of any irregularity in the motion transmitted by the gears will cause the scribing point, which is slightly eccentric, to move towards, or away from, the centre line of the spindle carrying G_2.

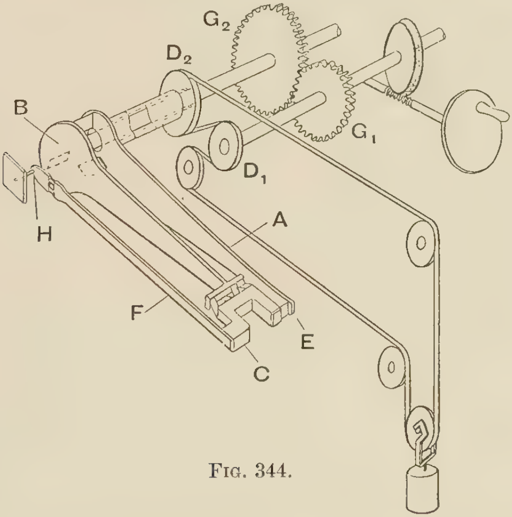


FIG. 344.

Since the arms A and B are carried round as the gears rotate, the scribing point H will also revolve about the axis of G_2, but its path will only be circular when the motion of the gears is exactly uniform. Ordinarily, it will describe an irregular curve, which is traced on a fixed, smoked-glass plate. An example of such a curve is shown enlarged in Fig. 345.

Such records can be examined very conveniently by enlarging them fifty times on a horizontal projection apparatus. The combined mechanical and optical magnification is then such, that a relative motion error between the gears of one minute of arc is represented by a linear radial distance of 0·85 inch on the screen.

The example shown was obtained from a pair of spur gears having 35 and 70 teeth. The record covers two complete revolutions of the larger gear, and the close agreement shown by the irregularities of the two outlines testifies to the accuracy of the scheme. The curves for the two revolutions are separated one from the other and

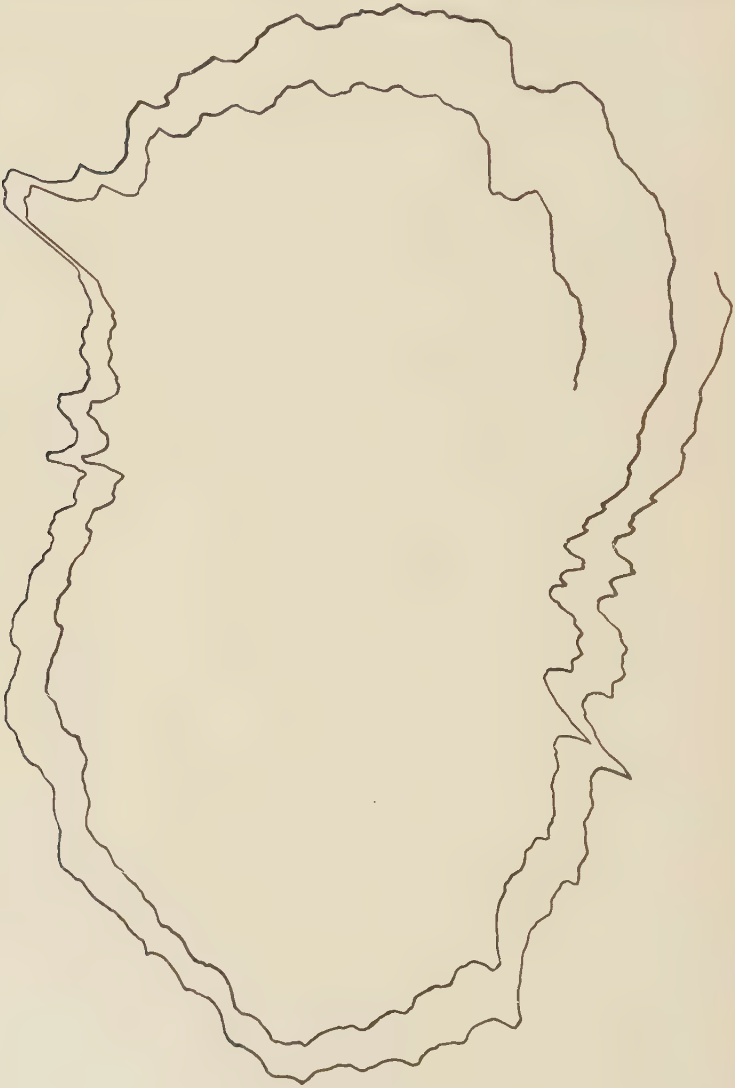


FIG. 345.

made to follow in the manner of a spiral, by making the ratio between the diameters of the discs D_1 and D_2 (Fig. 344) slightly different from that of the gears themselves. This has the effect of giving the scribing point a slow, but strictly uniform, progressive radial movement superimposed upon the movements arising from the interaction of the gears.

In cases where the number of teeth of the larger gear is not a multiple of that of the smaller one, exact similarity between two or more successive outlines is not to be expected, since the same teeth will not mesh together every time.

It need hardly be pointed out that, whilst this scheme of accurately recording the interaction between two gears gives evidence as to the aggregate effect of all the various errors present in the teeth, it is of very little use in providing information as to the extent of individual errors. For this, recourse has to be had to the various analytical tests described earlier. By substituting for one of the gears a good master gear of known errors, the scheme provides a simple method of comparing members of a batch of gears, and forming some early opinion of their running qualities as regards freedom from noise and vibration.

Hob-Measuring Machine.

Although gear-cutting hobs can be tested with the addition of certain fittings to the gear-testing machine described above, it was considered desirable, at the National Physical Laboratory, to construct a special machine for that purpose. Whilst adhering to the general principles of the earlier machine, Tomlinson was able to effect considerable simplification in the design, as will be evident from Fig. 346.

The hob under test is mounted between centres and is coupled at the left-hand end to a spindle carrying on its outer end a wheel and sine arm, by means of which the hob can be accurately rotated through given angles, just as in the gear-measuring machine. The actual measurements are made on traces of the teeth accurately recorded on a smoked-glass plate by means of a pantograph mechanism, similar in construction to that described in connection with the gear machine. The mechanism is capable of rotation about a horizontal pin at right angles to the hob axis, so that the plane of motion can be set square to the helix of the hob teeth. A sine bar is attached to the framework of the pantograph to facilitate this setting. Movements of the pantograph in a direction parallel to the hob axis are provided for by mounting it on a ground bar, supported in a pair of vees and capable of endwise movement by means of a micrometer, the two-inch range of which can be increased by the insertion of block gauges between the contacts.

The method of obtaining parallelism between the hob axis and the longitudinal traverse of the pantograph is of interest. The base of the apparatus comprises a well-finished surface plate (Fig. 346A), along the back of which is screwed a straight-edge. The bases of the headstocks carrying the centres have their front and back edges finished parallel to the line of centres, and are bolted to the surface plate at a suitable distance apart with their back edges in contact with the straight-edge. In a similar manner, the axis of the ground

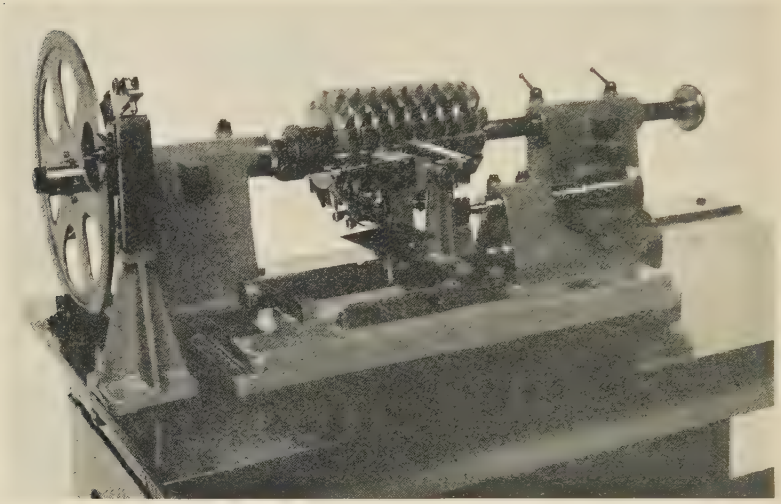


FIG. 346.

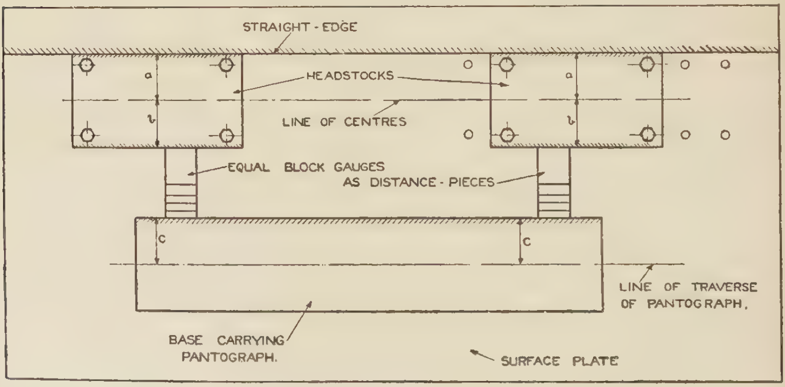

STRAIGHT - EDGE
HEADSTOCKS
a
b
a
b
LINE OF CENTRES
EQUAL BLOCK GAUGES AS DISTANCE - PIECES
c
c
LINE OF TRAVERSE OF PANTOGRAPH.
BASE CARRYING PANTOGRAPH.
SURFACE PLATE

FIG. 346A.

rod supporting the pantograph is set parallel to the rear edge of the block carrying that mechanism. Under these conditions, the insertion of a pair of equal distance-pieces, in the form of block gauges, between this carriage and the front edges of the headstocks, serves not only to ensure satisfactory parallelism between the hob axis and the traverse of the pantograph, but also as a ready means of adjusting the position of the latter to suit the diameter of the hob under test.

By combining the means provided for accurately rotating the hob and for translating the pantograph in a direction parallel to the hob axis, it is possible to carry out the following tests:

(*a*) Pitch of the teeth both around the helix and along the flute.
(*b*) Accuracy of spacing of the different threads of a multiple-start hob.
(*c*) Form of the teeth, including angle and symmetry.
(*d*) Relief of the teeth.
(*e*) Eccentricity of the teeth.
(*f*) Angular pitch of the cutting faces and helix angle of the flute.

As mentioned above, all the tests are carried out on pantograph traces of the teeth which are measured after enlarging them fifty times in a horizontal projection apparatus.

ADDITIONAL REFERENCES FOR CHAPTER XVI

" Tomlinson's Gear Measuring Machine," *Eng.*, vol. 116, p. 104 (1923).
" Tomlinson's Hob Measuring Machine," *Machinery*, vol. 28, p. 111 (1926).
Gear Testing Pamphlet, issued by Nat. Phy. Laboratory.

APPENDICES

APPENDIX I

WIRE AND PLATE GAUGES

Of the many series of wire and plate gauges in use in this country only two have received legal sanction: the Imperial Wire Gauge and the Birmingham Gauge. The former was authorized by an Order in Council, dated 23rd August 1883, and the latter at a subsequent date, 16th July 1914.

The following table gives the standardized equivalents in decimals of an inch for the various gauge numbers.

The recognized abbreviations for the two systems are "I.W.G." and "B.G."

Gauge Number.	Equivalents in Decimals of an inch.		Gauge Number.	Equivalents in Decimals of an inch.	
	Imperial Wire Gauge.	Birmingham Gauge.		Imperial Wire Gauge.	Birmingham Gauge.
15/0	..	1·000	1	0·300	0·3532
14/0	..	0·9583	2	0·276	0·3147
13/0	..	0·9167	3	0·252	0·2804
12/0	..	0·8750	4	0·232	0·250
11/0	..	0·8333	5	0·212	0·2225
10/0	..	0·7917	6	0·192	0·1981
9/0	..	0·750	7	0·176	0·1764
8/0	..	0·7083	8	0·160	0·1570
7/0	0·500	0·6666	9	0·144	0·1398
6/0	0·464	0·625	10	0·128	0·1250
5/0	0·432	0·5883	11	0·116	0·1113
4/0	0·400	0·5416	12	0·104	0·0991
3/0	0·372	0·500	13	0·092	0·0882
2/0	0·348	0·4452	14	0·080	0·0785
0	0·324	0·3964	15	0·072	0·0699

Gauge Number.	Equivalents in Decimals of an inch.	
	Imperial Wire Gauge.	Birmingham Gauge.
16	0·064	0·0625
17	0·056	0·0556
18	0·048	0·0495
19	0·040	0·0440
20	0·036	0·0392
21	0·032	0·0349
22	0·028	0·03125
23	0·024	0·02782
24	0·022	0·02476
25	0·020	0·02204
26	0·018	0·01961
27	0·0164	0·01745
28	0·0148	0·015625
29	0·0136	0·0139
30	0·0124	0·0123
31	0·0116	0·0110
32	0·0108	0·0098
33	0·0100	0·0087
34	0·0092	0·0077
35	0·0084	0·0069
36	0·0076	0·0061
37	0·0068	0·0054
38	0·0060	0·0048
39	0·0052	0·0043
40	0·0048	0·00386
41	0·0044	0·00343
42	0·0040	0·00306
43	0·0036	0·00272
44	0·0032	0·00242
45	0·0028	0·00215
46	0·0024	0·00192
47	0·0020	0·00170
48	0·0016	0·00152
49	0·0012	0·00135
50	0·0010	0·00120
51	..	0·00107
52	..	0·00095

Stubs' Steel Wire Gauge and Sizes of Twist Drills

Steel rod below about ¼-inch diameter is usually drawn to the following table of "gauges" which constitute the Stubs' Steel Wire System of Gauges.

The table also includes the equivalent sizes for the smaller sizes of twist drills which usually go by numbers.

It will be noted that, with four exceptions, where the sizes are the same, the drills are from 0·00025 to 0·004 inch larger than wire of the same gauge number.

Designating Number.	Equivalents in Decimals of an inch.	
	Stubs' Steel Wire Gauge.	Twist Drills.
1	0·227	0·228
2	0·219	0·221
3	0·212	0·213
4	0·207	0·209
5	0·204	0·2055
6	0·201	0·204

Designating Number.	Equivalents in Decimals of an inch.	
	Stubs' Steel Wire Gauge.	Twist Drills.
7	0·199	0·201
8	0·197	0·199
9	0·194	0·196
10	0·191	0·1935
11	0·188	0·191
12	0·185	0·189
13	0·182	0·185
14	0·180	0·182
15	0·178	0·180
16	0·175	0·177
17	0·172	0·173
18	0·168	0·1695
19	0·164	0·166
20	0·161	0·161
21	0·157	0·159
22	0·155	0·157
23	0·153	0·154
24	0·151	0·152
25	0·148	0·1495
26	0·146	0·147
27	0·143	0·144
28	0·139	0·1405
29	0·134	0·136
30	0·127	0·1285
31	0·120	0·120
32	0·115	0·116
33	0·112	0·113
34	0·110	0·111
35	0·108	0·110
36	0·106	0·1065
37	0·103	0·104
38	0·101	0·1015
39	0·099	0·0995
40	0.097	0·098
41	0·095	0·096
42	0·092	0·0935
43	0·088	0·089
44	0·085	0·086
45	0·081	0·082
46	0·079	0·081
47	0·077	0·0785
48	0·075	0·076
49	0·072	0·073
50	0·069	0·070
51	0·066	0·067
52	0·063	0·0635
53	0·058	0·0595
54	0·055	0·055
55	0·050	0·052
56	0·045	0·0465
57	0·042	0·043
58	0·041	0·042
59	0·040	0·041
60	0·039	0·040
61	0·038	0·039
62	0·037	0·038
63	0·036	0·037
64	0·035	0·036
65	0·033	0·035
66	0·032	0·033
67	0·031	0·032
68	0·030	0·031
69	0·029	0·02925
70	0·027	0·028
71	0·026	0·026
72	0·024	0·025
73	0·023	0·024
74	0·022	0·0225
75	0·020	0·021
76	0·018	0·020
77	0·016	0·018
78	0·015	0·016
79	0·014	0·0145
80	0·013	0·0135

APPENDIX II

RESULTS OF MEASUREMENTS OF A ONE-INCH CYLINDRICAL RING GAUGE BY VARIOUS METHODS

Measurements on "Chord Contact" Internal Machine.*

Mean diameter of balls on rod $=0{\cdot}09378$ inch.

Theoretical length of rod for 5 to 1 magnification

$$=0{\cdot}09378+\frac{1}{5}\sqrt{24}(1-0{\cdot}09378)$$
$$=0{\cdot}98169.$$

Actual measured length of rod used $=0{\cdot}98173$, at 62° F.

Theoretical displacement of correct length rod

$$=\sqrt{(1-0{\cdot}09378)^2-(0{\cdot}98169-0{\cdot}09378)^2}$$
$$=0{\cdot}1812.$$

Reading of micrometer head with rod in lower position in ring $=0{\cdot}3963$.

Reading of micrometer head with rod in upper position, after raising lever by the theoretical amount $0{\cdot}1812$ $=0{\cdot}5781$.

Difference between micrometer readings $=0{\cdot}1818$.

$\therefore$ Displacement of rod in ring is less than the theoretical amount $(0{\cdot}1812)$ by $\frac{1}{5}(0{\cdot}1818-0{\cdot}1812)$, *i.e.* $0{\cdot}00012$.

Since the actual length of the rod differs from the theoretical length by $+0{\cdot}00004$, a correction has to be applied to the error in displacement, thus :

We have, from p. 182,

$$h=\sqrt{(\mathrm{D}-d)^2-\mathrm{L}^2}.$$
$$\therefore \frac{dh}{d\mathrm{L}}=-\frac{\mathrm{L}}{h}=-5 \text{ approximately.}$$

Hence, correction $=+5\times0{\cdot}00004$
$=+0{\cdot}00020.$

$\therefore$ True error in displacement h,

$$=-0{\cdot}00012+0{\cdot}00020$$
$$=+0{\cdot}00008.$$

$\therefore$ Error in diameter of ring from the nominal size, one inch,

$$=+\frac{1}{5}\times0{\cdot}00008$$
$$=+0{\cdot}00002.$$

$\therefore$ Size of ring at centre

$=$ **1·00002 inch at 62° F.**

---

* For description see p. 182.

Measurements on "Displacement" Internal Machine.*

Size of standard plug used = 0·99998 inch at 62° F.

Left Side.		Right Side.		Sum of Micrometer Readings.
Block Gauges on Anvil.	Micrometer Reading.	Block Gauges on Anvil.	Micrometer Reading.	
Readings on Standard Plug :				
0·105	0·40260	0·107	0·36160	0·76420
Readings on Ring Gauge at centre :				
1 + 0·105	0·40703	1 + 0·107	0·35713	0·76416
Check Readings on Standard Plug :				
0·105	0·45572	0·107	0·30847	0·76419

Diameter of ring gauge at centre = sum of displacements of carriage minus size of standard plug

$= 2 \times 1$ inch block gauge $+ 0{\cdot}76419_5 - 0{\cdot}76416 - 0{\cdot}99998$
$= 2 \times 0{\cdot}99999_7 - 0{\cdot}99994_5$
= 1·00005 inch at 62° F.

Measurements in La Société Genevoise Machine Using Special Attachments.†

Size of block gauges used for forming standard gap gauge = 1·00000 inch at 62° F.

Micrometer reading on gap gauge . .	0·32482 inch,
,, ,, at centre of ring gauge .	0·32486 ,,
Check reading on gap gauge . . .	0·32482 ,,

∴ Size of ring gauge at centre

$= 1{\cdot}00000 + 0{\cdot}32486 - 0{\cdot}32482$
= 1·00004 inch at 62° F.

---

[*] For description see p. 185.
[†] For description see p. 180.

Summary of Results.

	Diameter of ring at centre (inches).
Chord contact machine	1·00002
Displacement machine	1·00005
Société Genevoise machine	1·00004
Mean . .	**1·00004** inch at 62° F.

It will be noted that the maximum difference between the results obtained on the three machines is only 0·00003 inch. The mean result is probably accurate to within ±0·00001 inch.

APPENDIX III

MATHEMATICAL INVESTIGATION OF THE FORM OF A STRAIGHT-EDGE BENDING UNDER ITS OWN WEIGHT, WHEN SUPPORTED HORIZONTALLY ON TWO SYMMETRICALLY PLACED SUPPORTS.

The straight-edge is assumed uniform in section, and the supports are placed symmetrically; a tangent to the bar at its centre will be horizontal. Fig. 347 shows one half of the bar, A being one point of support. y is taken positive downwards.

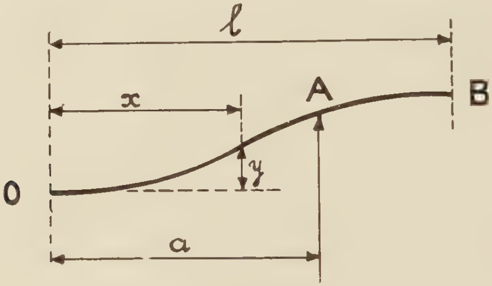


FIG. 347.

Let $l=\frac{1}{2}$ length of the straight-edge,
$a=$distance from centre to one of the two symmetrically placed supports.

The following formulae are given in the *Proceedings of the Physical Society of London* (vol. xviii. p. 35), in a paper by Dr. Chree.

Between O and A,

$$y=\frac{w}{\mathrm{EI}}\left\{\tfrac{1}{2}l(\tfrac{1}{2}l-a)x^2+\frac{x^4}{24}\right\}.$$

Between A and B,

$$y=\frac{w}{\mathrm{EI}}\times\frac{1}{24}\left\{4la^3-l^4+4lx(l^2-3a^2)+(l-x)^4\right\},$$

where x is distance measured from O as origin,

y is vertical displacement taken as positive downwards,

I is moment of inertia of cross section about an axis through its C. of G. and perpendicular to plane of bending $\left(=\frac{bd^3}{12}\right.$, where b is the thickness and d the depth of the straight-edge).

w is weight per unit length.

Values for a particular straight-edge:

$b=0{\cdot}125''$.
$d=3{\cdot}0478''$.
$w=1\times3{\cdot}0478\times0{\cdot}125\times0{\cdot}288=0{\cdot}109721$ lbs. per inch.
$\mathrm{E}=30{,}000{,}000$ lbs. per square inch.

$$\log\frac{w}{\mathrm{EI}}=\bar{8}{\cdot}0934794.$$

$$\log\frac{w}{\mathrm{EI}}\times\frac{1}{24}=10{\cdot}7132682.$$

When a is chosen equal to $\frac{l}{\sqrt{3}}$, *i.e.* when the supports are at the "Airy" points, then the straight-edge is horizontal at the ends.

For this particular position of the supports the results shown in Table I have been calculated.

TABLE I

x in inches.	y in inches.
0	0·0
5	−0·00001
10	−0·00006
15	−0·00011
20	−0·00016
25	−0·00019
30	−0·00020
35	−0·00020
36	−0·00020

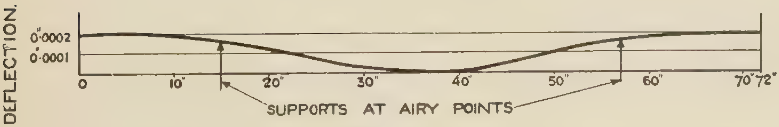


FIG. 348.

The theoretical flexure of the straight-edge, when supported at the "Airy" points, is shown in Fig. 348, which is plotted from Table I.

Effect of varying the Position of the symmetrically placed Supports on the Elastic Deformation of a Bar of Uniform Section, due to bending under its own Weight.

Between O and A, *i.e.* between the centre and one of the supports (Fig. 347),

$$y=\frac{w}{\mathrm{EI}}\left\{\tfrac{1}{2}l(\tfrac{1}{2}l-a)x^2+\frac{x^4}{24}\right\},$$

$$\frac{dy}{dx}=\frac{w}{\mathrm{EI}}\left\{\tfrac{1}{2}l^2x-lax+\frac{x^3}{6}\right\},$$

$$\frac{d^2y}{dx^2}=\frac{w}{\mathrm{EI}}\left\{\tfrac{1}{2}l^2-la+\frac{x^2}{2}\right\}.$$

The slope, $\frac{dy}{dx}$, is zero at the points given by the equation

$$\tfrac{1}{2}l^2x-lax+\frac{x^3}{6}=0\,;$$

i.e. when $x=0$, or $\sqrt{6la-3l^2}$.

There is a limit to the possible values of $\frac{a}{l}$ if there is to be another place beside the centre, and within the points of support, where the bar is horizontal—the value for x must lie between 0 and a.

If $x=0$, then $\frac{a}{l}=0{\cdot}5$.

If $x=a$, then $\frac{a}{l}=0$ or $3-\sqrt{6}$, *i.e.* 0 or 0·5505.

The value $x=0$ in the second set corresponds to the case where the bar is supported at the centre only. The values of $\frac{a}{l}$, to give a second horizontal point between the centre and the support, lie between the limits 0·5 and 0·5505.

If $\frac{a}{l}\overset{=}{<}0{\cdot}5$, then the bar is horizontal at the centre only.

If $\frac{a}{l}$ lies between 0·5 and 0·5505, the bar is horizontal also at those points between the centre and the supports where $x=\sqrt{6la-3l^2}$

If $\frac{a}{l}=0{\cdot}5505$, then the bar is horizontal at the points of support.

Between A and B, that is, beyond the points of support,

$$y=\frac{w}{\mathrm{EI}}\times\frac{1}{24}\left\{4la^3-l^4+4lx(l^2-3a^2)+(l-x)^4\right\},$$

$$\frac{dy}{dx}=\frac{w}{\text{EI}}\times\frac{1}{24}\left\{4l(l^2-3a^2)-4(l-x)^3\right\},$$

$$\frac{d^2y}{dx^2}=\frac{w}{\text{EI}}\times\frac{1}{24}\left\{12(l-x)^2\right\}.$$

The bar will be horizontal in this portion at a point given by $\frac{dy}{dx}=0$, *i.e.* $4l(l^2-3a^2)-4(l-x)^3=0.$

This gives $x=l-\sqrt[3]{l^3-3a^2l}.$

The limiting values for x over this portion of the bar are $x=a$ and $x=l$.

The permissible values of $\frac{a}{l}$ given by these conditions are between 0·5505 and $0{\cdot}5773_5$.

If $\frac{a}{l}=0{\cdot}5505$, then the bar is horizontal over the support. This agrees, as it should, with the result previously obtained.

If $\frac{a}{l}$ lies between 0·5505 and $0{\cdot}5773_5$, then the bar is horizontal at the positions given by $x=l-\sqrt[3]{l^3-3a^2l}.$

If $\frac{a}{l}=0{\cdot}5773_5$, then the bar is horizontal at the ends.

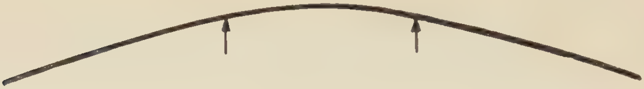
If $\frac{a}{l}>0{\cdot}5773_5$, the bar is not horizontal at any point beyond the support.

These results are illustrated in the diagrams in Fig. 349, where the bending is represented diagrammatically to a large scale.

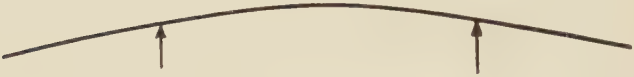
Considering the particular straight-edge referred to on p. 341, the values of y at the end, and at the points where $\frac{dy}{dx}=0$, have been calculated for a series of values of $\frac{a}{l}$ including the critical values. (The value of y at the centre of the bar is always zero.)

These values are given in Table II, together with the maximum deviation of the bar from the mean line, as illustrated in Fig. 350.

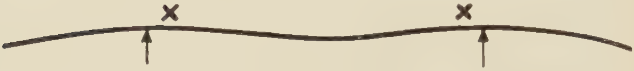
[Fig. 349.



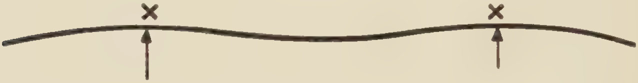
$\frac{a}{l} < 0{\cdot}5$. Bar horizontal at centre only.



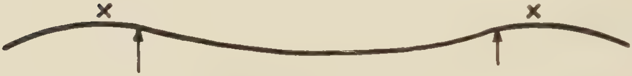
$\frac{a}{l} = 0{\cdot}5$. Bar still horizontal at centre only.



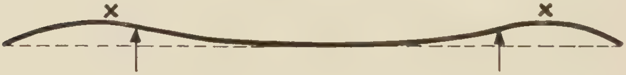
$\frac{a}{l}$ between $0{\cdot}5$ and $0{\cdot}5505$. Bar horizontal at centre and at two points between supports.



$\frac{a}{l} = 0{\cdot}5505$. Bar horizontal at centre and over supports.

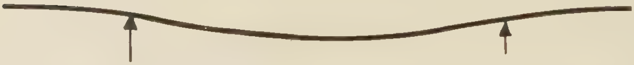


$\frac{a}{l}$ between $0{\cdot}5505$ and $0{\cdot}5537$. Bar horizontal at centre and also at two points outside the supports.

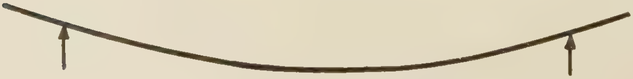


$\frac{a}{l} = 0{\cdot}5537$. Bar horizontal at centre and at two points outside the supports. Ends of bar at the same height as centre.

When $\frac{a}{l} < 0{\cdot}5537$ the centre is higher than the ends; when $> 0{\cdot}5537$ the centre is lower than the ends.



$\frac{a}{l} = 0{\cdot}57735$ ("Airy" points). Bar horizontal at the centre and ends.



$\frac{a}{l} > 0{\cdot}57735$. Bar horizontal at centre only.

Fig. 349.

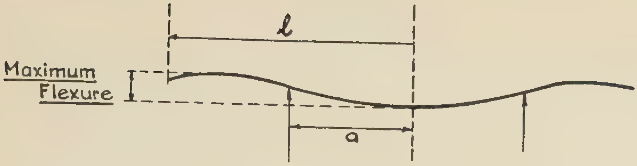


Fig. 350.

TABLE II

Values of y for various values of $\frac{a}{l}$.

$\frac{a}{l}$.	Deflection at End in inches.	Deflection where $dy/dx=0$, in inches.	Maximum Deviation from Mean Line, *i.e.* $\frac{1}{2}\times$ maximum flexure (Fig. 350).
0	+0·00260	..	±0·00130
·2	+0·00220	..	±0·00110
·3	+0·00176	..	±0·00088
·4	+0·00115	..	±0·00057
·5	+0·00045	..	±0·00022
·525	+0·00023	−0·00002	±0·00012
·5505	+0·00003	−0·00008	±0·00004
·5625	−0·00007	−0·00012	±0·00006
·57735	−0·00020	−0·00020	±0·00010
·6	−0·00040	..	±0·00020
·8	−0·00230	..	±0·00115
·9	−0·00330	..	±0·00165
1·0	−0·00435	..	±0·00217

The following investigation serves to determine the value of $\frac{a}{l}$ for which the elastic flexure is least.

Referring to Fig. 351, it will be seen that the minimum flexure of the bar takes place for a value of $\frac{a}{l}$ falling somewhere between 0·5 and 0·6. To determine this value of $\frac{a}{l}$, the region from 0·5 to 0·6 has been investigated at intervals of 0·01, and the values obtained are shown plotted in Fig. 352.

The position of the supports for the minimum flexure of the straightedge is given by this curve as approximately $\frac{a}{l}=0{\cdot}555$.

In this position, the distance from the highest to the lowest points is given by the curve as $2\times0{\cdot}00004_5$, *i.e.* 0·00009 inch.

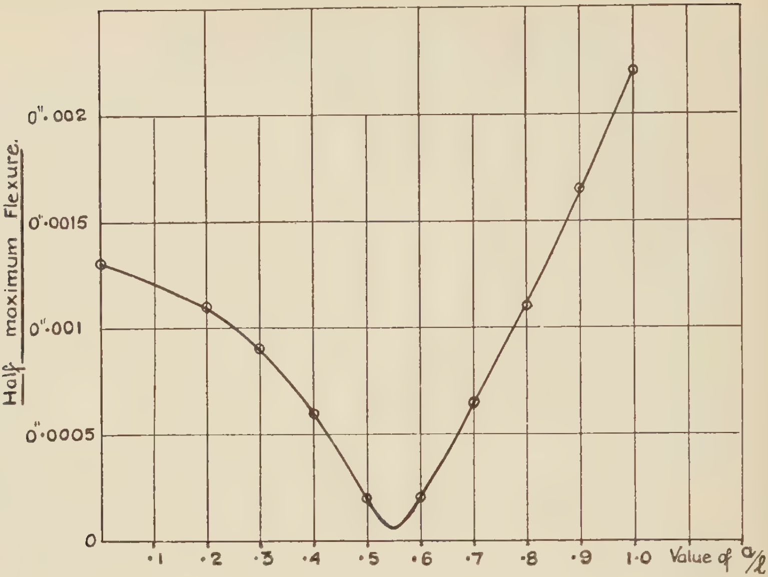


FIG. 351.

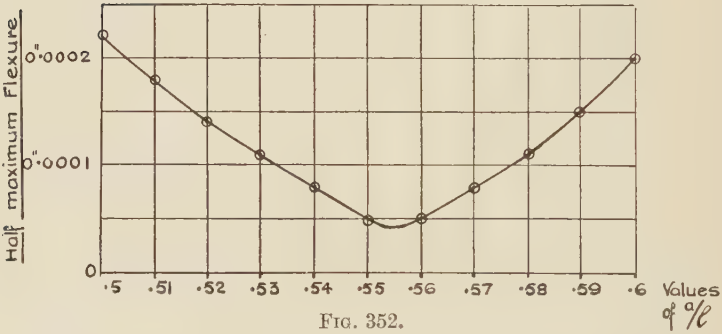


FIG. 352.

Now the value of $\frac{a}{l}$ for which the ends of the bar are at the same height as the centre, is given by the equation

$$4\left(\frac{a}{l}\right)^3 - 12\left(\frac{a}{l}\right)^2 + 3 = 0.$$

Solved by Horner's method, this gives

$$\frac{a}{l} = 0{\cdot}5537.$$

For this value of $\frac{a}{l}$, the deflection at the points where $\frac{dy}{dx} = 0$ is equal to $-0{\cdot}00009$ inch.

It will be noted that this value of $\frac{a}{l}$ agrees very closely with the one obtained from the curve; moreover, the flexure is also in agreement.

It appears, therefore, that the straight-edge will have the least flexure when the supports are at a distance apart given by approximately 0·554 of its length, and in this position the ends will be at the same height as the centre point.

When the straight-edge is supported at the "Airy" points, the maximum flexure is of the order of 0·0002 inch (see Fig. 348), *i.e.* approximately double the minimum smallest value as found above.

APPENDIX IV

NOTE ON THE TESTING OF A CIRCULAR DIVIDING MACHINE

In general, a circular dividing machine is supplied with a divided circle on the toothed disc, and this may be used as a reference in calibrating the toothed disc. The divided circle would probably be cut by a master dividing engine, and so, in general, would be more accurate than the toothed disc of the machine.

Calibration of the Divided Circle.

A modification of the ordinary comparator method for calibrating a straight scale is used. Two micrometer microscopes, L and R in Fig. 353, are mounted with their cross-wires parallel to the divisions of the circle. The microscopes are first fixed 30° apart, L being over 0° and R over 330°, and the readings l_1 and r_1 noted. The disc is rotated until the 330° division is under L and the 300° division under R, and new

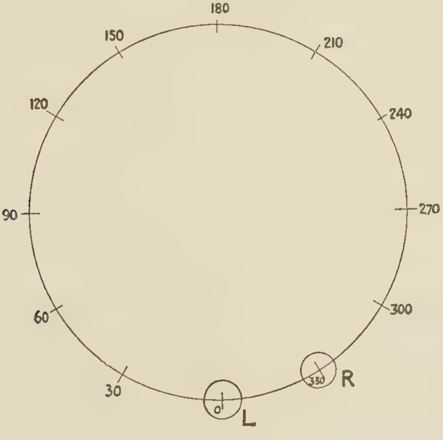


Fig. 353.

readings l_2 and r_2 are taken. This operation is continued until the 30° division is under L and the 0° division under R.

The differences

$$l_1 - r_1,$$
$$l_2 - r_2, \text{ etc.},$$

are then calculated, and the mean of these differences $(l - r)$ is taken. Then, since the scale is a circular one, the errors in the 30° intervals of the scale are given by

0° to 330° . . . . . $(l_1 - r_1) - (l - r)$,
330° to 300° . . . . . $(l_2 - r_2) - (l - r)$, etc.,

and the total error of the scale at any point, measured from 0° in the opposite direction to that in which the disc is rotated during the calibration, is given by

$$\Sigma\{(l_1 - r_1) - (l - r)\}.$$

This procedure gives the error at every 30° measured from 0°.

A similar set of readings is taken to provide the errors every 30° measured from 10°, and a third for every 30° measured from 20°. We then have the errors at the following points :

SET I.	(0)	30	60	90	120	150	180
SET II.	(10)	40	70	100	130	160	
SET III.	(20)	50	80	110	140	170	

SET I.		210	240	270	300	330
SET II.	190	220	250	280	310	340
SET III.	200	230	260	290	320	350

In order to refer the errors in Sets II. and III. to the zero line, a further set of readings is taken with the microscopes fixed 40° apart. From these readings, the errors measured from 0° to the following points can be obtained by the method explained above :

(0°) 40° 80° 120° 160° 200° 240° 280° 320° (360°).

Of these, the 40°, 160° and 280° points serve to tie all the points of Set II. back to zero, whilst the 80°, 200° and 320° points do likewise for Set III. In addition, the results at the 120° and 240° points serve as a check on the values found in Set I.

The above information is therefore sufficient to calculate the errors at every 10° round the circle.

Calibration of Toothed Disc with Respect to Divided Circle.

To calibrate the toothed disc, the worm-screw mechanism for driving the disc is utilised. For one complete revolution of the worm-screw (or for any multiple of one complete revolution), the toothed disc is advanced through a circumferential distance equal to the pitch of the tooth (or teeth) traversed. Thus the position of every tooth on the disc may be referred to the divided circle, but if it is only desired to calibrate the disc at every 5°, the following procedure is adopted. The worm-screw mechanism is set so that the screw may be rotated the exact amount required to advance the toothed disc through a nominal 5°, say from 0° to 5°. A single micrometer microscope is then set over the 0° division, and the reading a_0 is taken. The disc is then advanced through nominally 5° by means of the worm-screw mechanism, and the reading a_5 taken. This operation is continued until the disc has made one complete revolution, and then a few extra readings may be taken to ensure that the worm-screw mechanism has been accurately set in order that the scale may be accurately " closed ".

Let a be the mean of the readings a_0, a_5, a_{10} . . . a_{355}. Then the errors in " pitch " of the toothed disc, referred to the divided circle, are given by

$$a - a_0,$$
$$a - a_5,$$
$$a - a_{10}, \text{ etc.}$$

Note change of sign due to reversal by microscope.)

These readings would give a true calibration curve for the toothed disc if the divided circle were correct, but if errors have previously been found in the circle, the " pitch " errors of the disc must be corrected accordingly.

See also, Chap. IV. (The Divided Circle), *Optical Measuring Instruments*, L. C. Martin (Blackie and Sons, Ltd., 1924).

INDEX

Acme thread, gauge for, 81
Adjustments, fine, methods of obtaining, 284
Ageing surface plates, 192
Aldis spherometer, 53
Alignment, principle of, in instrument design, 271
Almond micrometer, manufacture of (ref.), 57
Angle gauges, Johansson, 139
— plate, universal, Société Genevoise, 118
— plates, 149
Angles, methods of testing and setting out, 124
—, tools for setting and measuring, 75
—, use of cylinders and block gauges for setting out, 142
" Autocollimating Telescope " (ref.), 217
Autocollimation test for straightness, 205

Balls, steel, use of for internal measurements, 165
—, —, use of for measuring taper ring gauges, 92
Bar-micrometer, 41
Barnes, M. M., improvement in micrometers, 25
Barrell, H., measurement of quartz fibres, 263
Beck, Messrs. R. and J., microscope for measuring wire, 236
Birmingham Wire Gauge (B.G.), 82, 335
Block gauges, use of for internal measurements, 163
Boring tool, adjustable, 110
Brinell impressions, instrument for measuring, 226
Brookes, A. J. C., 116, 193, 274
— — adjustable type of gap gauge, 10
Brown and Sharpe bevel protractor, 124
— — — callipers, 168
— — — height gauge, 70
Brown and Sharpe internal micrometer, 169
— — — micrometer heads, 36
— — — special type micrometer, 32
— — — straight-edge, 198
— — — type of micrometer, 25, 26
" Button " method of setting out jigs, 107

Calliper, Zeiss optical gear-tooth, 289
Calliper gauge, 69
Callipers, 78
—, use of for internal measurement, 162
Cambridge " crack " micrometer, 54
Cambridge Instrument Co., apparatus for testing flatness, 212
— — —, machine for measuring fine fibres, 263
— — —, travelling microscope, 218
Castellation gauges, measurement of, 100
Chesterman improved wire gauge, 83
— wedge gauge, 72
Circular dividing machine, note on testing, 347
— — —, Société Genevoise, 129
— — plate, Pratt and Whitney, 122
— — table, Société Genevoise type, 118, 128
— graduations, apparatus for testing, 131
Clamps, tool-makers', 76
Clinometer for gauge-testing, N.P.L. type, 133
—, precision type, by Société Genevoise, 134
Compound-slide table, Johansson, 110
Cooke, Troughton and Simms Ltd., adjustable level, 136
Corrector bars, 114, 283. (Also Vol. I.)
Crack micrometer by Cambridge Instrument Co., 54
Crossed-strip hinge, 281
Cylinder gauge, " Subito ", 175

D'Arsonval galvanometer, 253
Darwin, Horace, instrument design, 266

Depth gauge, Zeiss form, 85
— gauges, 18
— micrometers, 52
Design of measuring instruments, 266
  (refs.), 288
Differential micrometer screw, 38
"Disc" method of setting out jigs, 108
Dividers, 78
Dividing head, Zeiss, 126
— machine, circular, 129, 347
Dowling, J. J., "ultra-micrometer," 250
Drill gauge, Zeiss optical form, 86
Drills, gauge sizes of, 336

Eden, E. M., improved method for "line to line" settings, 65
—, —, internal measuring machine, 185
—, —, method of measuring fine wire, 258
—, —, original work on projection apparatus, 227
—, —, use of flexible strips on measuring instruments, 279
Einthoven galvanometer, 253, 257
Elastic deformation of gap gauges, 11
Electrical contact, using valve, 244
— measuring devices, 214
Errors of micrometer screws, 47
Extensometer, optical (ref.), 243
—, telemeter type, 256
Eyeglasses, 68

Feeler gauges, 80
Fine adjustments, types of, 284
Flat surfaces, generation of, 190
Flatness, tests for, 190
—, — — (refs.), 217
Flexure of straight-edge, investigation of, 340
Form gauges, 88
Freedom, degrees of, 267
Friction drive on micrometers, 27
Fuse, position gauge for, 22

Gap gauge, adjustable type (ref.), 23
— —, Brookes' adjustable type, 10
— —, Société Genevoise adjustable type, 10
— —, Wickman adjustable type, 8
— gauges, adjustable limit, 7
— —, built-up type, 7
— —, elastic deformation of, 11
— —, machine for setting, 12
— —, solid types, 6
— —, "Subito" indicator type, 16
— —, type by Greenfield Tap and Die Corporation, 11
— —, Zeiss indicator type, 17
Gaps, adjustable taper, 143
Gauge clinometer, N.P.L. type, 133
—, cylinder, "Subito," 175
—, "Maire", for internal measurement, 167
—, Taft-Peirce expanding plug, 167
—, thickness, 71
—, vernier height and depth, 70
—, wedge type, 72
—, Zeiss optical form for drills, 86
Gauges, adjustable limit gap, 7
—, block, use of for internal measurements, 163
—, castellation, measurement of, 100
—, depth, 18, 70, 85
—, feeler, 80
— for pitch of threads, 80
— for wire and plate, 82
—, form, 88
—, "form of head", measurement of, 97
—, gap, 5
—, Hoffmann roller type, 89
—, internal limit, 1
—, limit, types of, 1
—, — gap, built-up type, 7
—, — —, solid types of, 6
—, pin type, 161
—, plate, 82
—, plug limit, 1
—, position, 21, 88
—, —, manufacture of, 106
—, —, measurement of, 98
—, profile, 20
—, —, measurement and manufacture of (refs.), 105
—, —, measurement of, 95
—, spline, measurement of, 99
—, —, (refs.), 105
—, taper, 19
—, — plate, measurement of, 94
—, — plug, measurement of, 89
—, — ring, measurement of, 91
—, radius, 80
—, —, measurement of, 103
—, ring, measurement of, 160, 338
—, serration, 100
—, vernier calliper, 69
Gear-grinding machines (refs.), 310
— profile tester, Maag, 294
— teeth, shape of, 323
— —, symmetry of, 320
— testing apparatus, Saurer, 299
— — machine, Tomlinson's (N.P.L.), 311
— — machine, Wickman, 306
— — —, Zeiss, 301
— — machines (refs.), 310
— tooth calliper, Zeiss, 289

Gear tooth measurement, Maag, 292, 294
Gears, bevel, measurement of, 301, 327
—, helical, measurement of, 326
—, measurement of, 289, 311
—, — — motion between, 327
Geometric location, 266
— slides, 268
Glasses, magnifying, 67
Graduation of micrometers, 27
Grant, C. H., flexure of straight-edge, 199
Greenfield Tap and Die Corporation type of limit gap gauge, 11
Group records of gear teeth, 317

Height and depth gauge, vernier type, 70
Herbert, Messrs. Alfred, optical measuring machine, 224
Hilger, Messrs. Adam, optical flats, 196
Hirth type minimeter for internal measurement, 171
Hob-measuring machine, 331
Hockaday, A. J., arrangement for testing flatness, 204
Hoffmann roller gauges, 89
— — —, use of, for internal measurements, 164
Hole, slot and plane location, 267
Holes, small, measurement of (ref.), 189

Imperial Wire Gauge (I.W.G.), 82, 335
Index-plates, 108
Indicating instruments for internal measurements, 171
Indicator on Zeiss micrometer, 33, 40
Indicators, test, 85
Instruments, design of (refs.), 288
—, optical, 218
—, workshop measuring, 74
Internal callipers, Brown and Sharpe micrometer type, 168
— comparator by Zeiss, 176
— gauge, Johansson type (ref.), 189
— limit gauges, 1
— measurement using three-point contact, 177
— measurements, 160
— — by indicating instruments, 171
— —, use of measuring machines for, 180
— measuring machines, 180, 181, 182, 185
— micrometer, Brown and Sharpe type, 169
— —, Newall type, 168
— —, Zeiss type, 170
Involute testing machine, Zeiss, 295

Jig-boring machine, Carson type (ref.), 123
— — —, Pratt and Whitney type, 120
— — —, (refs.), 123
— — and measuring machines, Société Genevoise types, 111, 123
Jigs, button method of setting out, 107
—, disc method of setting out, 108
“ —, Fixtures and Templates ”, by Horner (ref.), 105
— and position gauges, manufacture of, 106
Johansson, adjustable type of internal gauge, 3
—, angle-gauges, 139
—, built-up micrometer, 42
—, compound-slide table, 110
— internal gauge (ref.), 189
Johnson, R. S., electric telemeter, 254

Lapping micrometer faces, 51 (ref.), 57
— pivots on projection apparatus, 235
Level, adjustable, 136
— comparator, use of for testing flatness, 204
— tubes, 136
— —, apparatus for testing, 137
— —, (refs.), 159
Levels, precision uses of (refs.), 217
—, sensitive, source of supply, 203
—, use of for testing straightness, 203
“ Lewbeck ” projection microscope, 236
Limit gauges, adjustable gap, 7
— —, built-up gap type, 7
— —, cylindrical-ended, 2
— —, depth, 18
— — for external measurements, 5
— —, internal, 1
— —, Johansson internal type, 3
— —, Pedersen internal type, 4
— —, Pitter internal type, 5
— —, plug, 1
— —, solid gap type, 6
— —, spherical-ended, 2
— —, taper, 19
— —, types of, 1
— —, use of for internal measurements, 160
— plug gauges, larger sizes of, 2
Liquid surfaces, use of for testing flatness, 206
Line-to-line settings, 64
Location, geometric, 266
Locking, methods of, 285

Maag gear profile tester, 294
— tooth-measuring instrument, 292
Magnifying glasses, 67

Magnifying glasses, Watson's binocular type, 67
"Maire" gauge for internal measurement, 167
Marking-off tools, 74
Measurements, internal, 160
— with scales, 58
Measuring faces of micrometers, accuracy and tests on, 45
— instruments, design of, 266
— —, electrical, 244
— —, optical types, 218
— —, workshop types, 74
— machine, Herbert's optical type, 224
— —, N.P.L. "Chord-Contact" type, 182
— —, N.P.L. "Displacement" type, 185
— —, N.P.L. type for gears, 311
— —, N.P.L. type for hobs, 331
— —, use of Société Genevoise type for internal measurements, 180
— —, use of Wickman type for internal measurements, 181
— — bed, tests on flatness, 209
— — beds, forms of, 274
— — —, flexure of, 274
— microscope, Cambridge Inst. Co. type, 218
— —, Société Genevoise rectangular co-ordinate type, 223
— —, Zeiss type, 226
Mercury cups, use of for testing flatness, 208
"Metr-inch" micrometer, 34
Micrometer, bar type, 41
—, Brown and Sharpe internal type, 169
—, — — — special type, 32
—, — — — type, 25, 26
—, Cambridge type for cracks, 54
—, differential screw, 38
—, direct reading type, 34
—, early type by James Watt, 24
—, enlarged dial fittings, 36
—, Johansson built-up type, 42
—, manufacture of Almond type (ref.), 57
—, "Metr-inch", 34
—, Newall internal type, 168
—, Palmer type, 25
—, Pitter built-up type, 43
—, Starrett type, 25
—, use of as comparator, 27
— with differential screw, 38
— with special faces, 35
—, Zeiss indicating anvil type, 33
—, — internal type, 170
Micrometer callipers, Brown and Sharpe internal type, 168
— heads, 36
— screws, form of thread, 283
— —, Johansson hardened type, 30
— —, materials for, 282
— —, "running-in", 282
— —, thrust of, 276
Micrometers, 24
—, accuracy of, 31
—, — of measuring faces, 45
—, — of reading, 47
—, adjustment for wear, 29
—, care of, 50
—, checking accuracy of, 52
— for depth measurements, 52
— for internal measurements, 168
—, lapping faces of, 51
—, larger types, 39
—, Slocomb special fitting for, 32
—, "springing" of (ref.), 57
—, testing accuracy of (ref.), 57
—, tests on, 44
—, — on accuracy of reading, 47
—, vernier on, 31
—, wear of (ref.), 57
Microscope, measuring, 218, 223
—, travelling, 218, 221
Microscopes, use of for gauge-testing (refs.), 243
Minimeter for internal measurements, 171
Mirrors, tilting, 280

Newall internal micrometer, 168
— surface plates, 191
N.P.L. chord-contact internal measuring machine, 182
— displacement type internal measuring machine, 185
— gauge clinometer, 133
— — projection apparatus, 229, 236
— gear measuring machine, 311
— travelling microscope, 221

"Odontometer", Pratt and Whitney, 291
Optical flats, use of for testing flatness, 195
— gear-tooth calliper, 289
— measuring instruments, 218
— methods of measurement (refs.), 243
— projection apparatus, 227
— — methods (refs.), 243
— —, theory of, 237

Palmer type of micrometer, 25
Pantograph, 313

Parallel motion, 279
Parallelism of surfaces, tests for, 213
Parallels, adjustable type, 78
"Passimeter", Zeiss, for internal measurements, 174
Pedersen adjustable type of internal gauge, 4
Periodic error, origin of, 277
— errors in micrometers, 47
Peters, O. S., electric telemeter, 254
Pin gauges, 161
Pitch of gears, measurement of, 293, 302, 306, 315
Pitter adjustable type of internal gauge, 5
— boring tool, 110
— built-up micrometer, 43
— rotatable surface plate, 193
— sine bar, 154, 157
Pivot lapping machine, 235
Plate gauges, 82, 94, 103, 335
Plug and spherical-ended rod gauges, difference in behaviour, 3
— gauge, Taft-Peirce expanding type, 167
— gauges, taper, 89
— — with detachable ends, 1
— limit gauges, 1
"Points" for use with block gauges, 163
Polar co-ordinate jig-boring machine, 112
Pollard, A. F. C., instrument design, 266
Position gauges, 21, 88
— —, measurement of, 98
Pratt and Whitney adjustable gap gauge, 9
— — — circular dividing plate, 122
— — — jig-boring machine, 120
— — — "Odontometer", 291
— — — sine plate, 154
Profile gauges, 20
— —, measurement of, 95
— —, measurement and manufacture of (refs.), 105
Projection apparatus, adaptation to pivot lapping, 235
— —, definition of images, 237
— —, lenses for, 229
— —, N.P.L. horizontal type, 229
— —, N.P.L. vertical type, 236
— —, optical, 227
— —, special uses of, 233
— —, (refs.), 243
Protractor, bevel, Brown and Sharpe, 124
—, —, Zeiss, 125
—, sine, 150

Quartz fibre, measurement of, 258

Radius gauges, 80
— —, measurement of, 103
Ratchet stop on micrometers, 27
Rayner, E. H., use of valve circuit for measurement, 246
Rheinberg scales, 63
Ridge, W. G., investigation on optical projection, 237
Ring and gap gauges, difference in behaviour of, 5
— gauge, comparison of measurements of, 338
— gauges, measurement of, 160
— taper gauges, 91
Roller gauges, Hoffmann type, 89
— —, Hoffmann, use of for internal measurements, 164
Rusting at contacts, 278

Saurer gear-testing apparatus, 299
Scale measurements, accuracy of, 58
Scales, measurements with, 58
— on glass and other materials, 63
—, steel, 59
—, use on measuring instruments, 68
Scribing block, 74
Screws, micrometer, 282
Sears, J. E., 68, 266, 284
Serration gauges, 100
Setting-up tools, 74
Settings, "line to line", accuracy of, 64
Sieves, testing by optical projection, 234
Sine bar, 151
— —, Johansson type, 153
— —, Pitter type, 154, 157
— — (refs.), 158
— —, Taft-Peirce type, 155
— plate, Pratt and Whitney type, 154
— protractor, 150
Slides, frictionless, 269
—, geometric, 268
Slocomb special fitting for micrometers, 32
Société Genevoise adjustable type gap gauge, 10
— — circular dividing machine, 129
— — — — plate, 118
— — instrument for testing circular scales, 131
— — internal measuring machine, 180
— — jig-boring and measuring machines, 111, 123
— — machine for setting gap gauges, 12
— — measuring microscope, 219
— — precision clinometer, 134
— — rectangular co-ordinate measuring microscope, 223

Société Genevoise universal angle plate, 118
Spherometer, 53
Spirit-levels, 136
— — (refs.), 159
— —, *see* Levels
Spline gauges, measurement of, 99
— — (refs.), 105
Squares, 75, 144
—, block type, 149, 150
—, methods of testing, 145
Starrett adjustable parallels, 78
— type of micrometer, 25
Steel balls, use of for internal measurements, 165
— strips, use of flexible, 279
Stott, V., research on pivots, 234
Straight-edge, mathematical investigation of flexure, 199, 340
Straight-edges, best position for supporting, 200, 340
— —, deflection of, 199
— —, methods of testing, 200
— —, types of, 197
Straightness, tests for, 190
Stubs' wire gauge, 336
"Subito" cylinder gauge, 175
"—" indicator type of gap gauge, 16
Surface plate, rotatable type, 192
— plates, ageing of, 192
— —, rigidity of, 193
— —, types of, 191
— —, use of for testing flatness, 195
Surfaces, method of generating, 190
—, tests for parallelism of, 213

Taft-Peirce adjustable taper gap gauge, 143
— — expanding plug gauge, 167
— — sine bar, 155
Taper gaps, adjustable, 143
— gauges, 19 (refs.), 105
— plate gauges, measurement of, 94
— plug gauges, measurement of, 89
— ring gauges, measurement of, 91
Tapes, steel measuring, 59
— for measuring motor rims, 63
—, use of for measuring cylinders, 60 (refs.), 73
Telemeters, electric, 254
Tenths, estimation of (ref.), 73
Test indicators, 85
Thickness, Zeiss instrument for measuring, 225
— gauge, 71, 80
Thomas, H. A., measurement of small displacements, 252
Thread-pitch gauges, 80
Tilting mirrors, 280
Tomlinson, G. A., gear-testing machine, 311
—, —, grid contact, 244
—, —, hob-measuring machine. 331
—, —, internal measuring machine, 182
—, —, investigation on optical projection, 237
—, —, measurement of fine wire, 259
—, —, method of testing squares, 148
Tool, adjustable boring, 110
Tools for marking-off and setting-up, 74
— for setting and measuring angles, 75
Trammels, 79
Travelling microscope, Cambridge Instrument Co., 218
— —, N.P.L. type, 221
Twist drills, sizes of, 336

"Ultra-micrometer", Dowling's, 250
"—", Whiddington's, 247

Valve circuits, use of, for measurement, 246, 247, 250, 252
Vee-blocks, 77
Vernier calliper gauge, 69
— height and depth gauge, 70
— on micrometers, 31
Vibrations, measurements of (ref.), 257
—, optical method of measuring (ref.), 243
Vices, tool-makers', 76

Watson's binocular magnifying glasses, 67
Watt, James, micrometer, 24
Watts, Messrs. E. R., spirit levels, 137
Wear, adjustment for, on micrometers, 29
Wedge gauges, 72
Wedges, folding type, for internal measurement, 162
Whiddington, R., "ultra-micrometer", 247
Whipple, R. S., instrument design, 266
Whitworth method of generating flat surfaces, 190
Wickman, A. C., adjustable limit gap gauge, 8
—, —, frictionless slide, 270
—, —, gear-testing machine, 306
—, —, internal measuring machine, 181
Wire gauge, Birmingham (B.G.), 82, 335
— —, Imperial Standard (I.W.G.), 82, 335
— —, Stubs', 336
— —, tapered slot type, 84

Wire gauges, 82
— —, use of, 83
—, measurement of, 258

Zeiss bevel protractor, 125
— depth gauge, 85
— dividing head, 126
— indicating micrometer, 33, 40
— indicator type of gap gauge, 17
Zeiss internal comparator, 176
— internal micrometer, 170
— involute testing machine, 295
— measuring microscope, 226
— optical drill gauge, 86
— — gear-testing machine, 301
— — gear-tooth calliper, 289
— "Passimeter", 174
— thickness measurer, 225

THE END

Printed in Great Britain by R. & R. Clark, Limited, *Edinburgh.*